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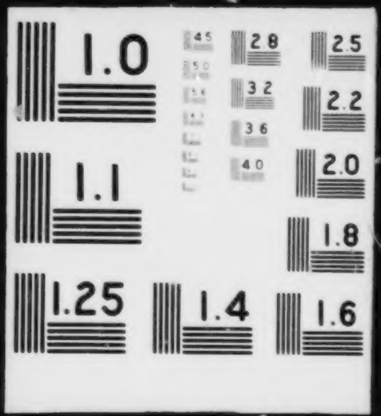
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NITRIFICATION AND DENITRIFICATION OF WASTE WATER

Final Report

Investigation Sponsored by Research Grant Number WP 01028
Environmental Protection Agency
Federal Water Quality Administration

by

Walter K. Johnson, Principal Investigator

and

George B. Vania

Sanitary Engineering Report Number 175 S

January 1, 1971

Sanitary Engineering Division
Department of Civil and Mineral Engineering
Institute of Technology
University of Minnesota
Minneapolis, Minnesota

January 1971

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16. Abstract

The denitrifciation ~~portion~~ of this work was accomplished by continuous flow reactor, a gravity solids-liquid separator, and sludge recycle, A portion of the raw wastewater was added as an external carbon source. By operating two completely mixed biological reactors in series it was possible to accomplish both nitrification and denifrification. Aeration times of 7-9 hours were used to produce a completely nitrified effluent at temperatures as low as 10-12°C. Denitrification was accomplished with a 1.3 hour mean reaction tank detention time at 20°C and in 2.6 hours at 10°C. Effluent ammonia nitrogen was that amount which was added to provide a carbon source. Therefore, addition of wastes with little or no ammonia nitrogen as a carbon source would produce an effluent nearly devoid of ammonia nitrogen. The BOD to nitrogen ratio was shown to be the critical parameter, inasmuch as high ratios would produce a high effluent carbon content, and low ratios resulted in complete denitrification. Keeping the ratio constant resulted in an effluent nitrogen concentration well below 1.0 mg/l. By this same analysis, the rate of nitate reduction was shown to be a linear function of the sludge loading rate. (Lowry-Texas)

17a. Descriptors *Nitrification, *Denitrification, Activated sludge, Municipal wastes, Ammonia, Nitrogen, Nitrates, Eutrophication, Temperature, Flow rate, Biochemical oxygen demand, Sludge, Waste water treatment, Tertiary treatment

17b. Identifiers
~~*Biochemical oxygen demand~~ to nitrogen ratio, Suspended solids
*BOD

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Students at the University of Minnesota who participated in the project included:

Bruce Bonde
Wallace Borene
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George Kriha
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I. NEED FOR NITROGEN REMOVAL

Nitrogen in various forms is one of the more abundant constituents of municipal wastewater and is only partially removed in conventional treatment processes(1).

Incomplete nitrogen removal may contribute to the degradation of receiving waters in several ways. Ammonia oxidation by nitrifying bacteria may result in serious oxygen deficiencies, and the general problem of eutrophication may be enhanced by making nitrogen more readily available for the growth of aquatic plants. In recognition of these possible effects water quality and effluent standards often include limitations on nitrogen concentrations, the consequence of which is to require higher removal percentages than now obtained from conventional treatment processes.

XI

II. DENITRIFICATION PROCESS FOR NITROGEN REMOVAL

A. Description of Process

Denitrification in wastewater treatment has been studied by a number of investigators(2,3,4,5,6,7,8,9,10,11), and several process schemes have been proposed to utilize microbial denitrification for nitrogen removal. Denitrification for nitrogen removal requires the reduction of nitrates to nitrogen gas, and such reduction is the "true dissimilatory nitrate reduction" pathway as defined by Verhoeven(12). Reduction is accomplished by heterotrophic facultative anaerobic species of bacteria which have the ability to replace oxygen with nitrate as the essential hydrogen acceptor in their metabolic processes(13). These ubiquitous microorganisms include many genera and the overall reaction by which nitrogen is removed is as follows:

$$2HNO_3 + 10H = N_2 + 6H_2O.$$

Because municipal wastewaters seldom contain appreciable concentrations of nitrogen in the nitrate form the nitrogen removal process by denitrification must be preceded by a nitrification process whereby essentially all of the nitrogen is converted to the nitrate form. It is generally accepted that the conventional activated sludge process should be used to produce a nitrified effluent, and the operating conditions required with the process to obtain such an effluent have been established by Downing, Painter and Knowles(14) and by Johnson & Schroepfer(2).

B. Kinetics of the Denitrification Process

1. Development

The denitrification process investigated in this research work involved a continuous flow reactor, gravity solids-liquid separation and sludge recycle. It has been shown(2) that rapid denitrification requires an external carbon source which may be a portion of the raw wastewater or an externally supplied organic compound. The flow diagram used is shown as Figure 1.

The similarity of the flow diagram to that of the activated sludge process is obvious and the two processes also usually have a common objective to yield an effluent having a low biochemical oxygen demand (BOD). The processes differ, however, in the dependency of input quantities. In the activated sludge process a carbon-containing substrate is an independent variable while dissolved oxygen, the hydrogen acceptor, is a dependent variable. From an economic standpoint an effort is made to minimize the oxygen input. In denitrification the roles of carbon and hydrogen acceptor are reversed. The nitrate ion as the hydrogen acceptor is an independent variable and the carbon substrate must be supplied in proportion to the nitrate.

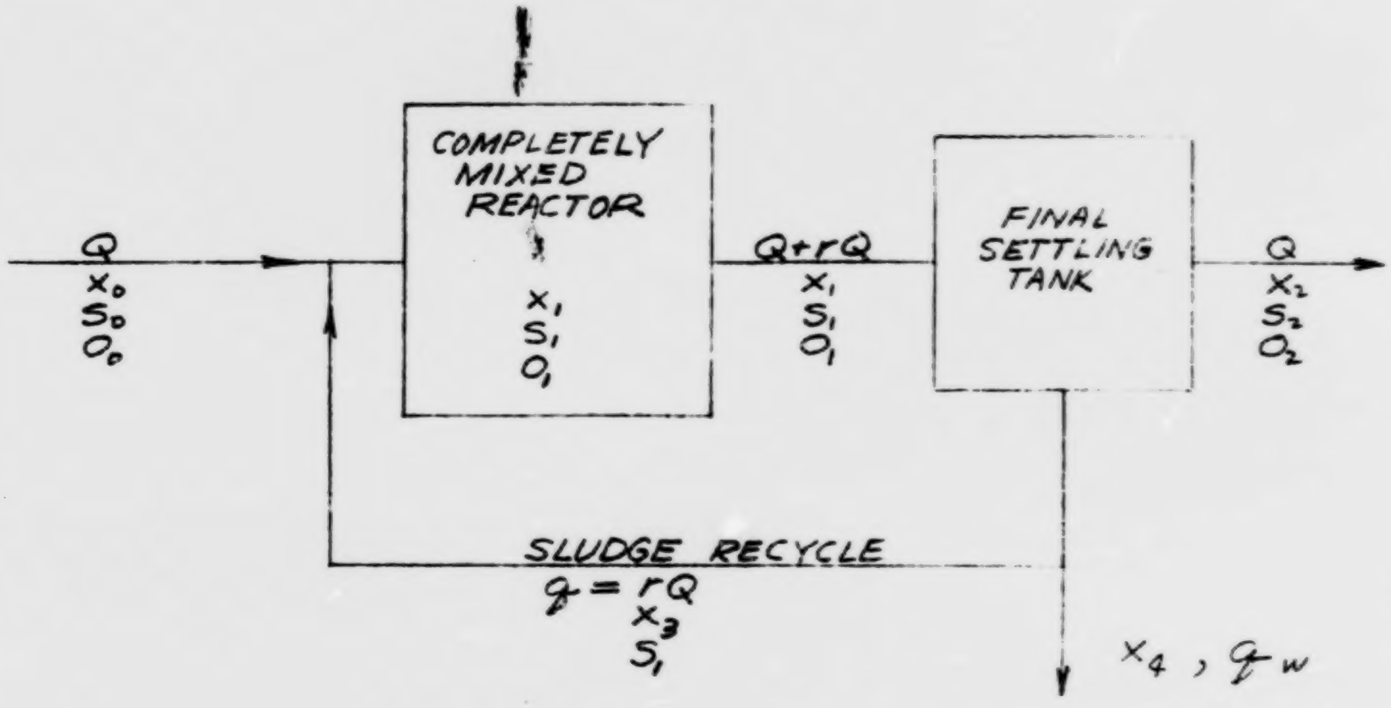
With these comparisons between the two processes the generally accepted theories of microbiological growth used to describe the activated sludge process may be applied to the denitrification process as proposed. Many investigators have described activated sludge kinetics in continuous flow cultures including McKinney(15), Eckenfelder & O'Connor(16), Schulze(17), Downing, Painter and Knowles(14) and Smith and Eilers(18). Three differential equations may be used to describe the interaction in a biological treatment process. The net rate of growth of microorganisms is usually given as:

$$(1)\ \frac{dx}{dt} = k_1 x - bx$$

where x_1 is the concentration of microorganisms, k_1 is the specific growth rate constant, and b is a decay constant.

The rate of disappearance of substrate may be described as:

$$(2)\ \frac{ds}{dt} = -\frac{1}{Y}\frac{dx}{dt}$$


COMPLETELY MIXED REACTOR
Q
x_0
S_0
O_0
x_1
S_1
O_1
$Q+rQ$
x_1
S_1
O_1
FINAL SETTLING TANK
Q
x_2
S_2
O_2
SLUDGE RECYCLE
$q = rQ$
x_3
S_1
x_4, q_w

$r = q/Q$

Q, q, q_w = FLOW RATES

x_0, x_1, x_2, x_3, x_4 = CONCENTRATIONS OF MICROORGANISMS

S_0, S_1, S_2 = CONCENTRATIONS OF SUBSTRATE

O_0, O_1, O_2 = CONCENTRATIONS OF DISSOLVED OXYGEN

FLOW DIAGRAM FOR DENITRIFICATION

FIGURE 1

where s is the substrate concentration and Y is the yield of microorganisms in terms of grams of microorganisms produced per gram of substrate used.

In an aerobic process the oxygen uptake rate may be presented as:

$$(3)\ \frac{dO}{dt} = a'\frac{ds}{dt} + b'x$$

where dO/dt is the rate of change of the dissolved oxygen concentration, a' is a constant describing the oxygen uptake proportional to the substrate removal, and b' is the endogenous oxygen demand constant. In the denitrification process a nitrate concentration or the oxygen equivalent of nitrate is substituted in the above equations for the oxygen concentration.

Although these three equations describe fundamentals of microbial growth, modifications are necessary when applying them to continuous flow denitrifying cultures in completely mixed systems when recycle is employed as shown in Figure 1.

Referring to Figure 1, a material balance for microbiological cell growth may be written as follows:

Change = Input - Output + Growth - Decay

$$V\frac{dx}{dt} = Qx_0 + rQx_3 - (1+r)\,Qx_1 + Vk_1x_1 - Vbx_1$$

or

$$\frac{dx}{dt} = \frac{Q}{V}\left[x_0 + rx_3 - (1+r)\,x_1\right] + k_1x_1 - bx_1.$$

For steady state and complete mixing, $\frac{dx}{dt} = o$, and assuming $x_0 = 0$:

$$(4)\ (1+r)\,x_1 - rx_3 = t(k_1x_1 - bx_1)$$

where V is the volume of the reactor and $t = \frac{V}{Q}$, the reactor detention time.

Referring again to Figure 1, a material balance for substrate is as follows:

Change = Input - Output - Removed

$$V\frac{ds}{dt} = QS_0 + rQS_1 - (1+r)QS_1 - \frac{Vk_1x_1}{Y}$$

or

$$\frac{ds}{dt} = \frac{Q}{V}(S_0 - S_1) - \frac{k_1x_1}{Y}.$$

For steady state and complete mixing, $ds/dt = o$:

$$(5)\ S_o - S_1 = \frac{tk_1x_1}{Y}.$$

Using the notation from Figure 1, a material balance for oxygen (nitrates) is written as:

Change = Input - Output - Removed

$$V\frac{dO}{dt} = QO_o - QO_1 - aQ(S_o-S_1) - bx_1V$$

For steady state and complete mixing, $dO/dt = 0$, and assuming $O_1 = 0$:

$$(6)\ O_o = a'(S_o-S_1) + b'x_1t$$

where a' and b' are oxygen (nitrate) use coefficients. It is assumed in the above equation that all oxygen added to the system is as an equivalent concentration in the raw flow.

Equations (4), (5), and (6) are the counterparts of the general equations (1), (2) and (3), and may be used directly in the analysis of the denitrification system under consideration. The design and operation of a denitrification system requires the determination and/or assumption of a number of parameters in the equations. Usually the unknown and the known or assumed values would be listed as follows:

Unknown parameters:

t = reactor detention time, days

x_1 = mixed liquor volatile suspended solids (MLVSS) concentration, mg/l

S_o = substrate concentration as the 5-day 20°C BOD (BOD_5), mg/l

Known or assumed parameters:

Q = total inflow excluding recycle, l/day

r = return sludge flow rate as fraction of raw flow

S_1 = effluent BOD_5, mg/l

x_3 = VSS concentration in return sludge, mg/l

O_o = equivalent oxygen concentration in raw flow, mg/l

Y = yield coefficient, mg VSS/mg BOD_5 removed

a' = coefficient of oxygen use by substrate, mg O/mg BOD_5 removed

b' = coefficient of oxygen use by endogenous metabolism, mg O/mg VSS/day

b = VSS decay rate, $days^{-1}$

k_1 = specific growth rate, $days^{-1}$

Assuming the validity of equations (4), (5) and (6), the unknown parameters may be determined from the solution of these equations simultaneously. This must be preceded, however, by assigning appropriate values to the remaining parameters, the most critical of which are O_o, Y, k_1, a', b' and b.

2. Oxygen Equivalent Available from Nitrates

Although the nitrate ion is used as the hydrogen acceptor the oxygen analogy may be used, and McCarty(11) and Barth(7) have shown that on an equivalent basis only 5/6 of the oxygen in the nitrate is available as an equivalent amount of dissolved oxygen. Consequently the O_o value is $\frac{48}{14} \times 5/6$ of the nitrate-N concentration which is to be reduced.

3. Yield

In a study of nitrate respiration by Aerobacter aerogenes using glucose as the carbon source by Hadjipetrou(19), yield coefficients were determined for three environments: anaerobic; anaerobic with nitrates; and aerobic. The respective yields were 0.14, 0.25, and 0.40 g cells/g glucose.

The relative magnitude of yields was particularly noted by Painter(20): that anaerobic systems have the lowest yields; and that yields from nitrate systems are less than those from aerobic systems and greater than anaerobic systems. Although no specific data from mixed cultures and wastewater substrates are available it is reasonable to assume that yield coefficients less than those from aerobic systems are appropriate. On this basis Y values of 0.2-0.4 would seem reasonable.

McCarty(11) studied the characteristics of several pure organic compounds with respect to denitrification and determined consumptive ratios for each. The consumptive ratio was defined as the ratio of the total quantity of an organic chemical consumed during denitrification to the stoichiometric requirement for denitrification and deoxygenation alone. The greater the ratio the greater chemical requirement for biological growth (synthesis). Because net synthesis does not directly require the uptake of nitrate, the lower the ratio the more efficiently a given chemical is being used in terms of reducing available nitrates. They found yields to vary considerably with the various organics tested and of course it is essential to consider yield variations when making economic studies of the process.

4. Growth Rate

Few data on the growth rate of denitrifers are available. General observations of denitrification systems in this and similar research efforts lead to the conclusion that rate constants only slightly below those found with aerobic systems should be used. In studies of the utilization of nitrate by Micrococcus dentrificans by Chang(21). There is the opportunity to compare growth rates under aerobic conditions with those under anaerobic conditions utilizing nitrates as the hydrogen acceptor.

Maximum rate constants determined from the data were 11.4 and 6.3 days^{-1} respectively. Studies by Schroeder & Busch$^{(22)}$ compared the rate of disappearance of glucose by dissolved oxygen and nitrate systems and the rates of glucose uptake were quite similar. It is possible to estimate a maximum rate constant of approximately 14 days^{-1} from the data. For activated sludge Downing and Wheatland$^{(23)}$ estimated a maximum rate constant of 4.8 days^{-1} and Smith$^{(18)}$ found with activated sludge and under particular conditions of analysis that the maximum rate constant varied from 3 to 8 days^{-1}. The Miohaelis-Menten expression for the microbial growth is usually used to relate specific growth rate (k_1) to maximum specific growth rate (km):

$$k_1 = \frac{k_m S}{K_s + s}$$

where K_s is the Michaelis constant and S the substrate concentration. Downing$^{(23)}$ found it reasonable to assume, as did Smith$^{(18)}$, a value for K_s for sewage of 150 mg/l BOD_5 where S also is in terms of BOD_5. If it is reasonable to assume k_m and K_s values of 4.8 days^{-1} and 150 mg/l BOD_5 respectively for aerobic systems, corresponding constants may be estimated at 2.5 days^{-1} and 150 mg/l BOD_5 for nitrate systems. Therefore in this analysis:

$$k_1 = \frac{2.5\ S}{150+S}$$

5. Oxygen Equivalent Required Per Unit of Substrate Removed

The utilisation of a carbon substrate in biological treatment processes is accomplished through a combination of oxidation to carbon dioxide and synthesis to new cells. Oxygen or nitrate is used in direct proportion to the oxidized substrate and in a nitrate respiration system it is particularly advantageous to minimize the ratio: substrate-used/nitrate-reduced. It was shown earlier from the work of Hadjipetrou(19) that for a given amount of substrate utilized the yield is less with nitrate respiration than with oxygen. Consistent with this observation it is appropriate that greater a' values should be used for nitrate systems than for aerobic processes. The a' values usually used with conventional activated sludge systems are of the order of 0.4 to 0.6 and consequently corresponding values for nitrate systems should be somewhat greater.

6. Endogenous Coefficients

No directly applicable data are available for the decay coefficient b, but a value of 0.1 as used in the activated sludge process should be reasonable. More critical is the endogenous nitrate reduction coefficient. In terms of oxygen equivalent, work by Johnson & Schroepfer(2) shows that the endogenous demand coefficient b' is of the order of 0.04.

7. Rate of Nitrate Reduction

The rate of nitrate reduction was expressed in equations 3 and 6 as a function of the rate of substrate removed and the weight of mixed liquor solids. As with oxygen uptake, the contribution of the endogenous demand to the rate of nitrate reduction is small compared to the nitrate demand of an actively metabolizing sludge. Therefore, the only way to maintain a high rate of nitrate reduction, which is desirable from an economic standpoint, is to have a high rate of substrate removal. McKinney(15) observed that growth rates are controlled by the Food/Microorganisms ratio, and since substrate removal rates are proportional to growth rates, the rate of nitrate reduction should be a function of this ratio. Eckenfelder(24) expressed the rate of nitrate removal (R) in terms of mg nitrate-N removed/g MLSS/hr, and data after Johnson & Schroepfer(2) presented in Figure 2 show this rate to be a linear function of the Food/Microorganisms ratio expressed as F or BOD/MLVSS: weight of BOD_5 applied to the reactor per day divided by the weight of MLVSS in the reactor. Milk solids were used as the carbon or BOD source. A line of regression through the points has the equation:

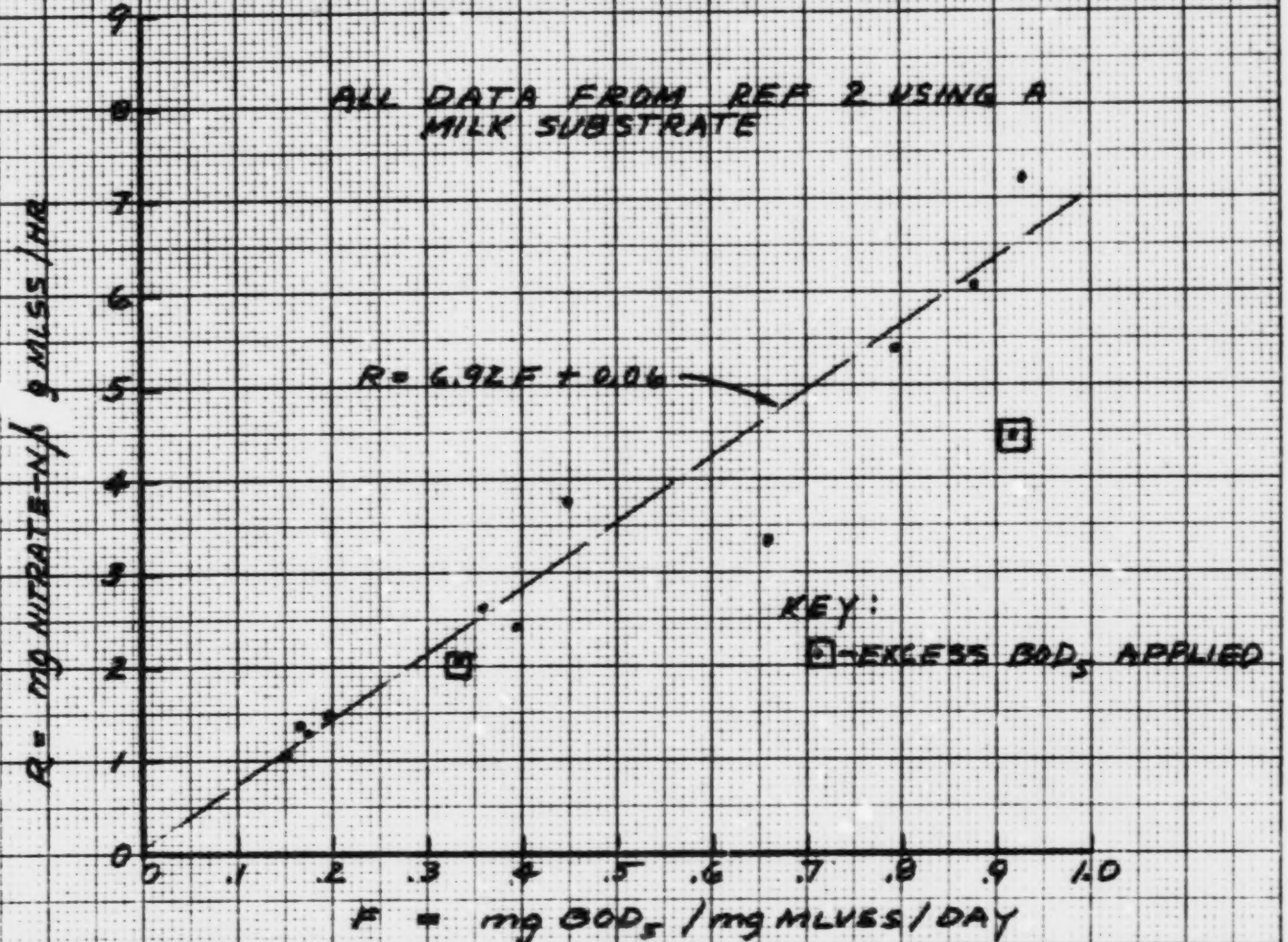
$$R = 6.92\ F + 0.06$$

and the correlation coefficient is 0.969. The intercept is essentially the endogenous nitrate reduction rate for this particular set of data. The data for the two enclosed points on Figure 2 were not considered in the calculations since they were obtained under conditions when excessive amounts of substrate were being applied to the reactor. It is apparent that at a given nitrate reduction rate the use of increasing concentrations of substrate would shift the data point progressively to the right and beyond equilibrium considerations as shown in Figure 2.

When effluent quality standards require nitrogen removal it is usually the case that effluent BOD_5's must also be low. Because both effluent quality and rate of nitrate reduction are functions of the BOD/MLVSS ratio, it is incompatible to expect high rates of nitrate reduction and yet obtain low effluent BOD's.

8. Ratios: Substrate Metabolized/Nitrate Reduced

The basic equations 3 and 6 require determining a constant relating the rate of degradation of substrate to the rate of nitrate reduction. Neglecting the endogenous demand this constant is an equilibrium ratio between the substrate utilized (to reduce the nitrates) and the nitrates reduced. The slope of the curve in Figure 2 is essentially that ratio. The BOD value used in Figure 2 includes that used for deoxygenation and consequently the BOD used only in the reduction of the nitrates cannot be obtained directly from the graph. Barth, Brenner and Lewis(7) in their



NITRATE REDUCTION RATE IN CONTINUOUS FLOW DENITRIFICATION

FIGURE 2

work with methanol expressed this as a methanol/nitrate-N ratio and concluded that a value of approximately 4 was required. Work reported by McCarty(11) showed that in semi-continuous operation of denitrification units using detention times of 10 to 30 days the methanol to nitrate ratio was only 2.48. The difference was in part attributed to the fact that the Barth(7) work may not have deducted that methanol required for deoxygenation. Another, and possibly more important factor contributing to the difference, is the fact that where long contact times are used there is always a greater proportion of net oxidation over synthesis resulting in the reduction of more nitrate per unit weight of substrate metabolized.

Work reported by Tamblyn and Sword(25) and Seidel and Crites(26) with the anaerobic filter confirmed McCarty's(11) work with respect to the required methanol/nitrate-N ratio. They were able to accomplish complete nitrate reduction with contact times of less than 2 hours and methanol/nitrate-N ratios of 2.5. The anaerobic filter may well be a more efficient unit for nitrate reduction than the completely mixed methanol system used by Barth(7) operating with a holding time of 3 hours and a methanol/nitrate-N ratio of 4.0. The difference in methanol requirements is most likely attributable to the differences in process yield. In nitrate reducing systems the yield from the anaerobic filter may be less than that from the completely mixed system just as trickling filter yields are less than those from activated sludge processes(27). Lower yields are characteristic of anaerobic systems and the anaerobic layer adjacent to the media in filter systems may account for the lower net yields.

From the discussion it is evident that a carbon source must be supplied to denitrify at a reasonably high rate, and a constant weight ratio of substrate to nitrate must be supplied. Carbon sources ranging from pure organics to municipal wastewaters may be used, and the substrate portion of the ratio may be expressed as actual weight of chemical, carbon content, COD or BOD. To enable the use of a common parameter for all carbon sources, a ratio of BOD_5 applied/nitrate-N removed (BOD/N) has been used in this work. The mean ratio required in the work presented in Figure 2 was 4.5 (range 4.0-4.9). The methanol/nitrate-N ratio converted to similar units using a BOD_5 of methanol of 0.835 g/g(28) is 3.3 from the work by Barth(7) and 2.1 after McCarty(11). It is likely that the ratio depends both on the substrate used and the biological system employed. With a particular system and substrate, one or two pilot tests would establish this ratio and the linear relationship between loading and rate of nitrate removal for use in the design of facilities.

9. Example of Use of Kinetic Equations

Using a flow diagram as presented in Figure 1 and data given previously by Johnson & Schroepfer(2): Test 30-3:

Assumed Values

S_1 = 10 mg/1 BOD_5

r = 0.35

x_3 = 8000 mg/1 MLVSS

$O_o = 19.1 \times \frac{48}{14} \times \frac{5}{6} = 55$ mg O/1

Y = 0.4 mg VSS/mg BOD_5

a' = 0.65 mg O/mg BOD_5

b' = 0.04 mg O/day/mg MLVSS

$b = 0.10\ \text{days}^{-1}$

$k_1 = \frac{2.5 \times 10}{150 + 10} = 0.16\ \text{days}^{-1}$

Unknown:

S_o, x_1, t

Equations:

$$(4)\ (1 + r)\ x_1 - rx_3 = t(k_1 x_1 - bx_1)$$

$$(5)\ (S_o - S_1) = \frac{tk_1 x_1}{Y}$$

$$(6)\ O_o = a'(S_o - S_1) + b'x_1 t$$

Subst in equations (4), (5) & (6):

$$(4a)\ 1.35\ x_1 - 2800 = 0.16\ x_1 t - 0.1\ x_1\ t = 0.06\ x_1 t$$

$$(5a)\ S_o = \frac{0.16\ x_1 t}{0.4} + 10$$

$$(6a)\ 55 = 0.65(S_o - 10) + 0.04\ x_1 t$$

Subst 5a in 6a:

$$55 = 0.26\ x_1 t + 0.04\ x_1 t$$

$$x_1 t = 183$$

Then S_o, x_1, and t are:

$$S_o = 83\ \text{mg/l BOD}_5$$

$$x_1 = \frac{2810}{1.35} = 2080\ \text{mg/l}$$

$$t = .089\ \text{days} = 2.1\ \text{hrs}$$

Then: $$\text{Ratio} = \frac{\text{BOD}_5}{\text{nitrate-N}} = \frac{83}{19.1} = 4.4$$

The actual data reported included a MLSS concentration of 2360 mg/l, a detention time of 2.2 hours and a BOD/N ratio of 4.2. Although the computed data compare well with the experimental data it is recognized that changes in the magnitude of the constants used in the equations may alter the results considerably. Nevertheless the values for the constants used in the equations are reasonable with respect to the data available at the present time, and the equations show a sound kinetic basis for describing characteristics of the denitrification process.

C. Process Economics

The carbon source and choice of process used for denitrification are the key factors in an engineering design situation and in a cost analysis. If no external carbon source is used and endogenous respiration is used for denitrification, large contact tanks and high capital costs are required. Reliance on endogenous respiration alone for dentrification has the additional disadvantage that ammonia-N is continually released as cellular solids are decomposed. The use of an additional carbon source will reduce the capital costs but may increase operating costs. If a raw municipal waste is used as the carbon source the percent nitrogen removal will be limited, and the purchase of organics such as methanol are costly. In any local situation it may be possible to obtain nitrogen deficient organics at a low cost and in turn alter the economics of the process.

Ideally, of course, a local supply of a nitrogen-deficient wastewater should be used, and in such situations the economic aspects of yield become important only with respect to sludge disposal considerations.

III. EXPERIMENTAL RESEARCH PROGRAM

The objectives of the test program were to more explicitly define the factors affecting nitrification and denitrification such as the effect of variable rates of flow, temperature, mixed liquor solids concentrations, reaction time, and dissolved oxygen in the system. Initially continuous flow tests were conducted in the laboratory with a synthetic wastewater to obtain sufficient information to design and operate a larger scale demonstration plant using a municipal wastewater as a substrate. Although factors affecting nitrification have been investigated previously by Johnson and Schroepfer(2) and particularly by Downing, Painter and Knowles(14), it was felt that the nitrification process for these particular operating conditions should be investigated as a preliminary to denitrification. The principal goal, however, was to study denitrification.

The initial tests are referred to as the Reactor Tests and the later tests are called the Demonstration Plant Tests.

IV. ANALYTICAL PROCEDURES

A. General

Whenever possible, analyses of the wastewaters were conducted in accordance with procedures published in Standard Methods(29). Where several procedures were given and when the procedure used was not as presented in Standard Methods(29), the particular methods employed are described in the following paragraphs. Colorimetric work was conducted with a Coleman Model 14 spectrophotometer.

B. Mixed Liquor Suspended Solids

Mixed liquor suspended solids were measured using 11.0 cm diameter glass fibre filter paper, Hurlbut Paper Co. No. 934-AH. The paper is non-hygroscopic and as such did not require drying prior to initial weighing. After obtaining the tare weight of the paper, the paper was placed in a Buchner funnel having a 9.1 cm inside diameter in order to form a cup with the paper. The measured sample was then filtered with the usual vacuum. The use of the glass paper enabled the determination of volatile content by burning at 600°C. Each paper was conveyed on a flat porcelain dish.

C. Dissolved Oxygen

Dissolved oxygen concentrations were obtained with a Precision Scientific Co. galvanic cell oxygen analyzer.

D. Nitrate Nitrogen

The phenoldisulfonic acid method was used.

E. Total Phosphorus

The procedure used was essentially that described by Menzel and Corwin(30) and Gales, Julian and Kroner(31) in which potassium persulfate is used. The orthophosphate was analyzed by the aminoaphtholsulfonic acid method(29).

V. REACTOR TESTS

A. General Conditions

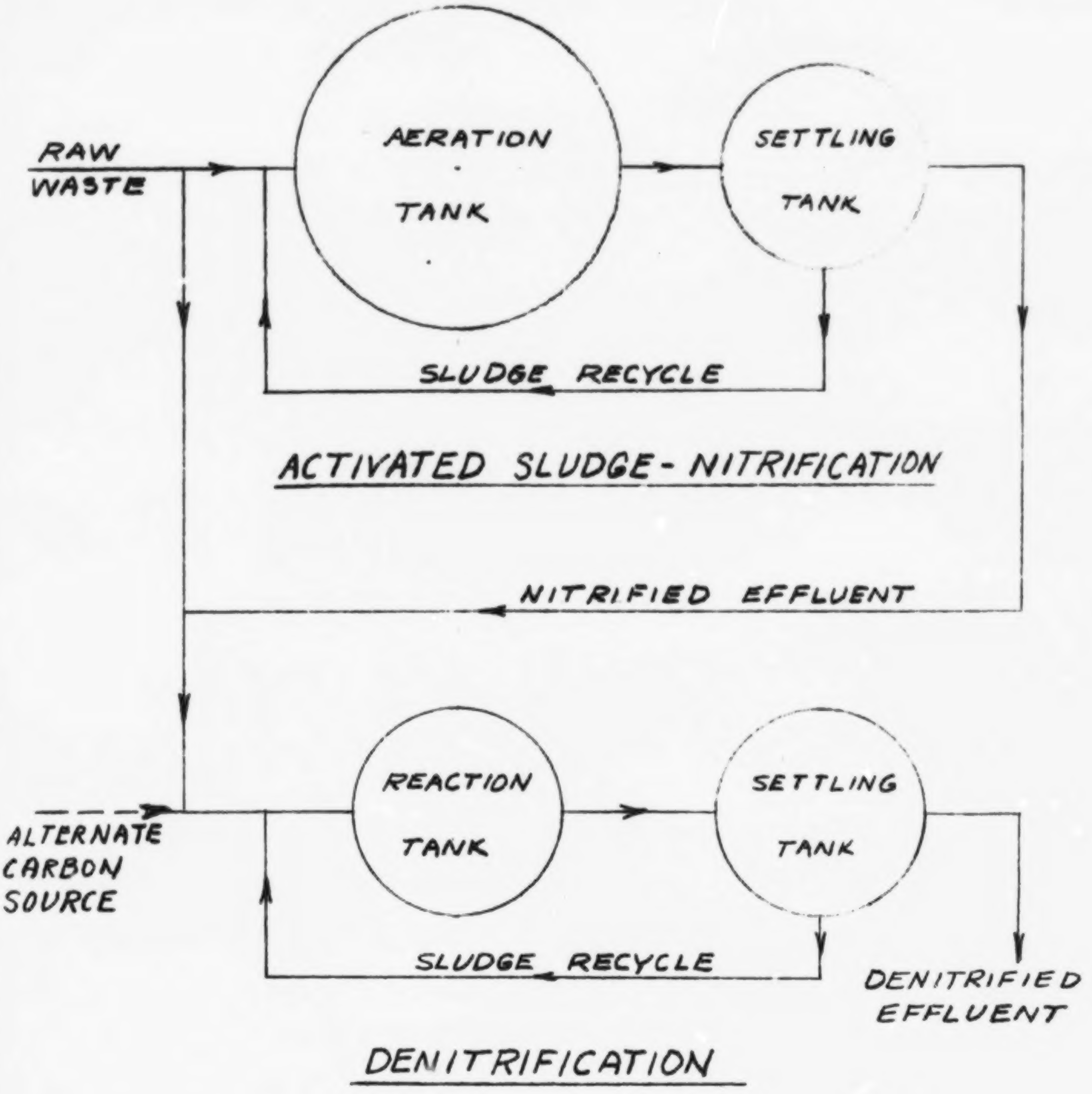
The Reactor Tests were conducted in the Sanitary Engineering Laboratory at the University of Minnesota. All tests were conducted with a synthetic wastewater under controlled temperature conditions and with continuous flow.

The basic process for studying nitrification was the activated sludge process. Similarly, the denitrification process was studied as an anaerobic version of the activated sludge process. These basic flow diagrams are shown in Figure 3. The activated sludge process needs no explanation but the denitrification process should have some clarification. The reaction tank of the denitrification process receives the nitrified effluent from the activated sludge process together with a limited amount of raw waste or other carbon-source material. Both the reaction tank and settling tank of the denitrification unit were sealed off from the atmosphere and interconnected. The gases taken off at the tope of the tubes were compressed and recirculated to the bottom of the reaction tank to provide mixing. After the initial use of oxygen in the system the recirculation gases were essentially molecular nitrogen (N_2) and the system was kept anaerobic.

B. Equipment

All reactor tests were conducted in a constant temperature room measuring 6 ft x 10 ft and as manufactured by the Hotpack Corp.

The reactor units were all plexiglass tubes, each either 2 inches or 3 inches in diameter, 4. ft long and having a wall thickness of 1/8 in. The bottom of each tube has a machined cone-shaped configuration. The bottom and several positions along the side were drilled and tapped with a ½ in pipe thread. Caps were made to fit both the 2 and 3 inch diameter tubes to enable sealing the tubes from the atmosphere. The details of the tubes and cap are


RAW WASTE
AERATION TANK
SETTLING TANK
SLUDGE RECYCLE
ACTIVATED SLUDGE- NITRIFICATION
NITRIFIED EFFLUENT
ALTERNATE CARBON SOURCE
REACTION TANK
SETTLING TANK
SLUDGE RECYCLE
DENITRIFIED EFFLUENT
DENITRIFICATION

FLOW DIAGRAMS

FIGURE 3

presented in Figure 4. The tubes were made for use either as aeration tanks or settling tanks and several tanks could be connected in series to increase total residence times. Tubes were interconnected with soft plastic vinyl tubing. Aeration was accomplished by insertion of a porous stone aerator at the bottom of the tube. The tubes were assembled on a rack to permit adjustment up or down according to the head requirements for gravity flow. A typical arrangement of the tubes and equipment is shown as Figure 5.

For the denitrification tests, mixing in the reaction tank was provided by recirculating the effluent gases in a closed system through the use of a Cole-Parmer Bantam Dyna-Vac laboratory pump.

All feed pumps and sludge recirculation pumps were of the Sigmamotor type with Zero-Max speed reducers. For variable flow operation the lever operator of the Zero-Max was interconnected with a clock-timer assembly such that the pumping rate varied in a sinusoidal pattern having one cycle over a 24-hour period. The equipment is as shown in Figure 6. The operation of the entire unit has been described and analyzed by Johnson(32).

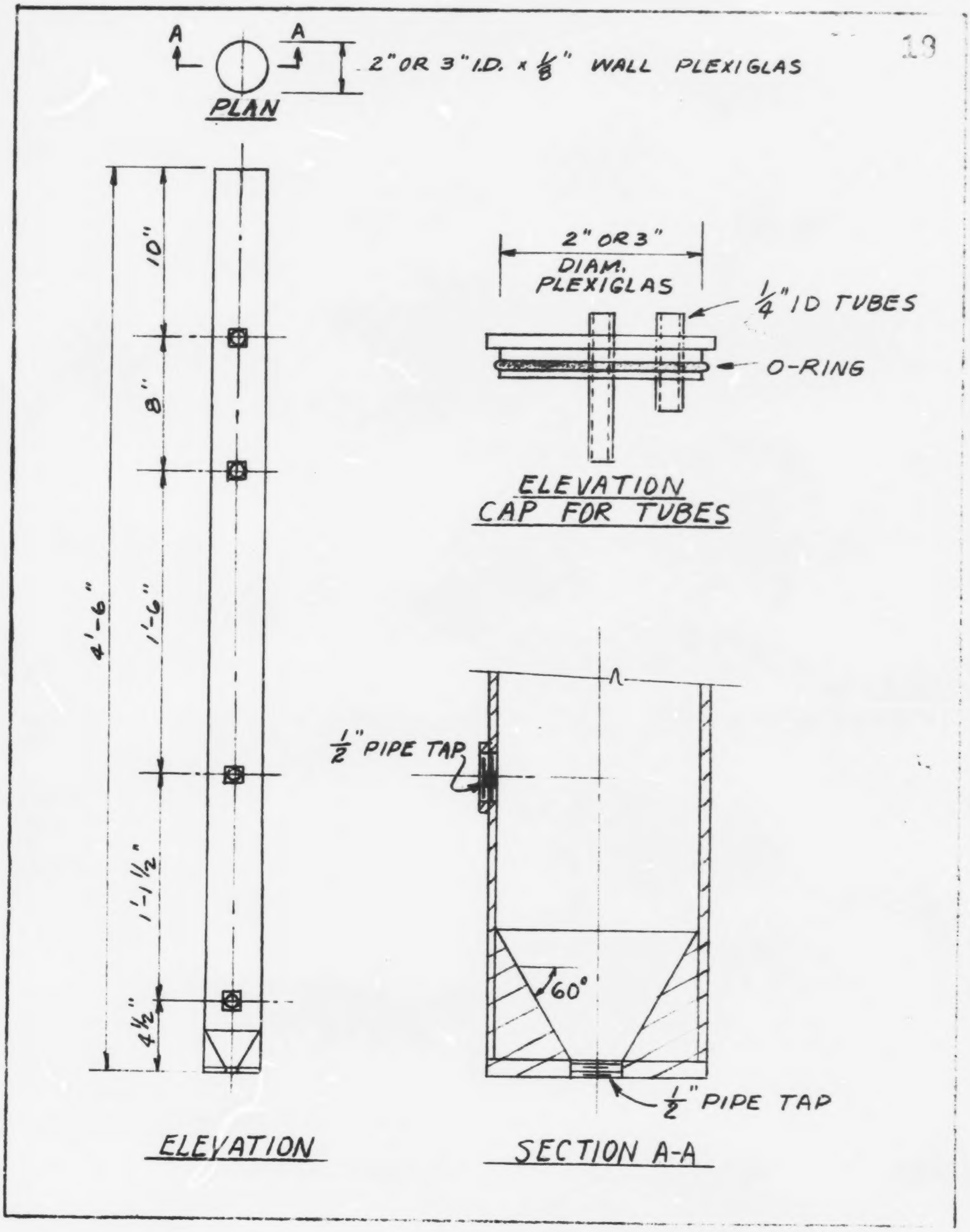
C. Procedures

1. General

Initially tests were conducted at 20°C to obtain background information on independent operations of the nitrification and denitrification processes. The majority of these tests were conducted with constant rates of flow, but for a few days variable flow was used.

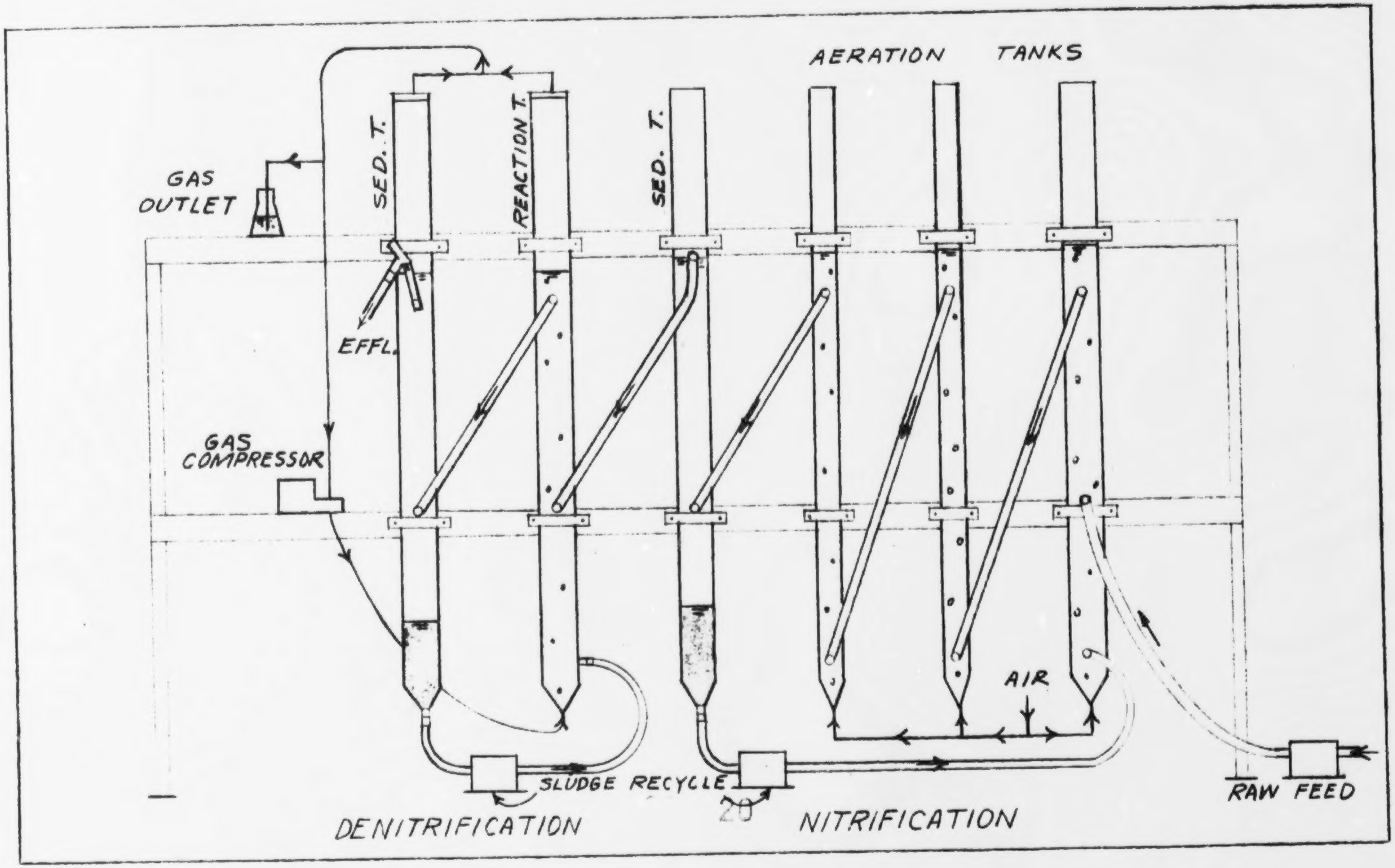
After conducting these initial tests, the nitrification and denitrification processes were then run in series at both constant and variable flow conditions at 20°C. Later, series tests of nitrification and denitrification at 10°C were conducted.

To be assured of having a supply of activated sludge solids on hand at all times a continuous flow conventional activated sludge "pilot plant" was kept


A
A
2" OR 3" I.D. x 1/8" WALL PLEXIGLAS
PLAN
10"
8"
4'-6"
1'-6"
1'-1 1/2"
4 1/2"
ELEVATION
2" OR 3"
DIAM. PLEXIGLAS
1/4" ID TUBES
O-RING
ELEVATION
CAP FOR TUBES
1/2" PIPE TAP
60°
1/2" PIPE TAP
SECTION A-A

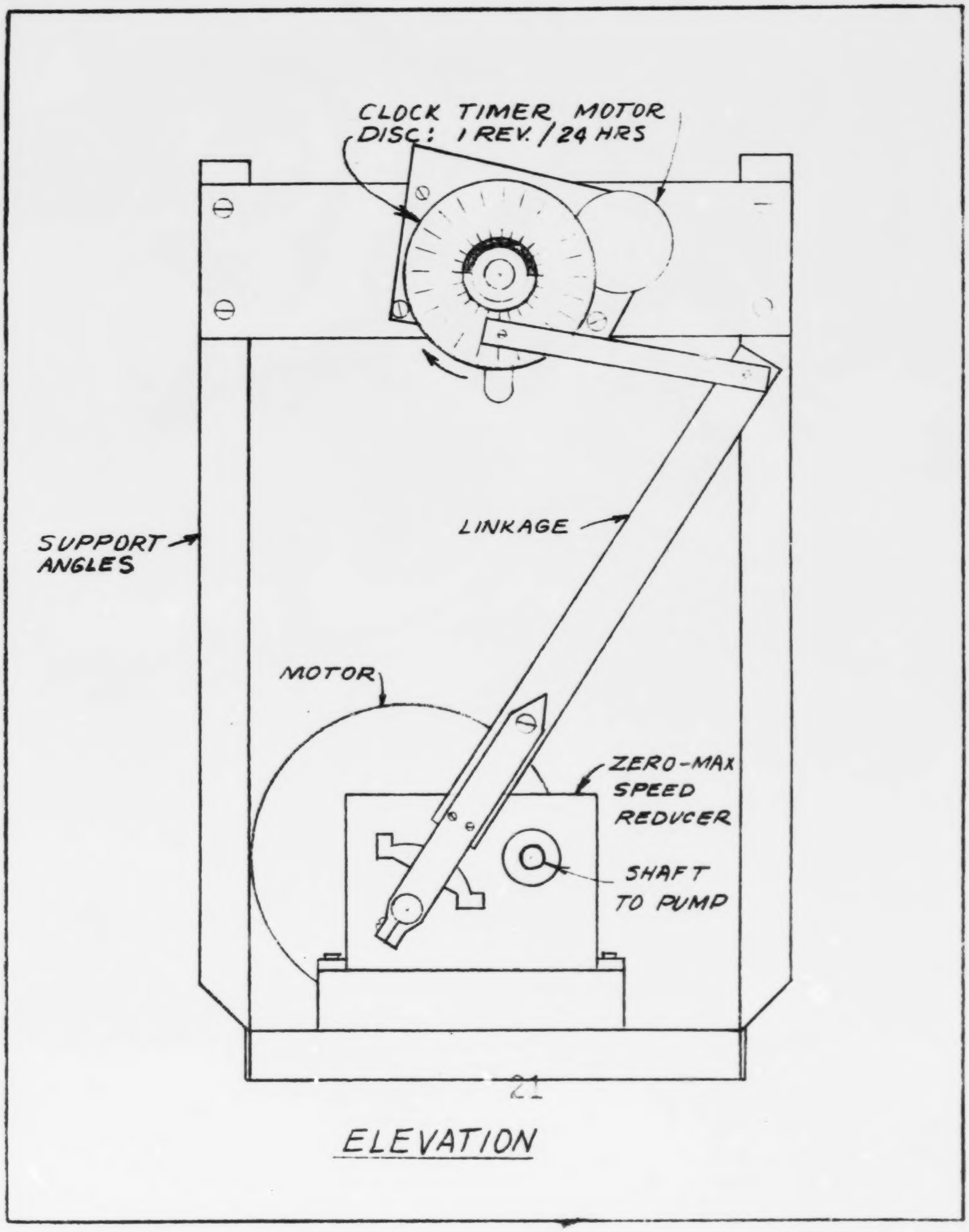
REACTOR TANKS - CONSTRUCTION DETAILS

FIGURE 4


AERATION TANKS
GAS OUTLET
SED. T.
REACTION T.
SED. T.
EFFL.
GAS COMPRESSOR
AIR
SLUDGE RECYCLE
20
RAW FEED
DENITRIFICATION
NITRIFICATION

ASSEMBLY OF REACTOR TUBES AND EQUIPMENT

FIGURE 5


CLOCK TIMER MOTOR
DISC: 1 REV./24 HRS
SUPPORT ANGLES
LINKAGE
MOTOR
ZERO-MAX SPEED REDUCER
SHAFT TO PUMP
ELEVATION

EQUIPMENT FOR VARIABLE-RATE PUMPING

FIGURE 6

in operation throughout the period of testing. The mixed liquor solids from this unit were used in the reactors. This equipment was described previously(2).

Unless otherwise shown, all physical, chemical and biological analyses were done using 24-hour composite samples. This was easily accomplished since the entire volume of effluent from any reactor system for a 24-hour period was collected in one container from which the samples were obtained.

All analytical work was done in the Sanitary Engineering Laboratories.

2. Substrate

a. Nitrification Tests

Solutions of dry milk solids were used as the basic raw waste and at times were supplemented with other constituents. Characteristics of dry milk solids are as shown in Table 1(33).

Table 1. Composition of dry milk solids

Constituent	Per cent by weight	Concentration in solution: 1g/gal
Butterfat	0.9	-
Protein	36.9	-
Lactose	50.5	-
Total solids	96.7	-
Organic solids	88.6	-
BOD (5-day, 20°C)	75.0	198 mg/l
Total nitrogen (N)		15.4 mg/l
Total phosphorus (P)		2.6 mg/l

The raw waste for the nitrification tests was a supplemented solution of dry milk solids consisting of:

Dry milk solids - 264 mg/l (1g/gal)

Sodium bicarbonate - 264 mg/l (1g/gal)

Ammonium sulfate - 56 mg/l

Dechlorinated City of Minneapolis tap water

This mixture is referred to as the standard milk solution (SM) with characteristics as shown in Table 2.

Table 2. Average analysis of synthetic wastewater (standard milk solution)

Chemical oxygen demand, COD	291 mg/l
Biochemical oxygen demand, BOD, 5-day, 20°C	198 mg/l
Ammonia and organic nitrogen-N	27 mg/l
Total alkalinity as $CaCO_3$	200 mg/l
Total residue	517 mg/l
Total phosphorus, P	2.6 mg/l

The waste was mixed and stored in plastic barrels from which it was pumped into the units.

b. Denitrification Tests

(1) Nitrate Solution

When separate denitrification tests were conducted the nitrate feed was in the form of a solution of sodium nitrate. The exact concentration varied between tests.

(2) Carbon Source

The carbonaceous material used as feed to the denitrification reactor was either a solution of milk solids or methanol. The milk solids were not supplemented with either sodium bicarbonate or ammonium sulfate. All solutions were made in dechlorinated City of Minneapolis tap water. The exact concentrations used varied between the tests.

The characteristics of methanol were assumed as follows:

Density:	0.791 g/ml
COD:	1.500 g/g
BOD_5(28):	0.835 g/g

Table 3. Listing of Reactor Tests

Test No.	Dates		Type[x] of test	Temp °C	Type[y] of flow	Feed[z] solution
	Start	End				
1	7.10.67	9. 8.67	N	20	C	SM
2a,b	7.10.67	9. 8.67	N	20	C	SM
3a,b,c	7.15.67	9. 8.67	N	20	C	SM
4	7.27.67	8.11.67	N	20	C	SM
5	9.12.67	10.13.67	N	20	C	SM
6	9.12.67	10.13.67	N	20	C	SM
7	10.13.67	10.26.67	N	20	C	SM
8	10.13.67	10.26.67	N	20	C	SM
9	10.25.67	10.31.67	D	20	C	MN
10	10.27.67	10.29.67	N	20	C	SM
11	10.27.67	10.29.67	N	20	C	SM
12	11. 7.67	11.22.67	D	20	C	MN
13a	11.14.67	11.30.67	N	20	C	SM
13b	11.30.67	12.11.67	N	20	V	SM
14	12. 5.67	12.14.67	D	20	C	MN5
15	12.18.67	1. 1.68	N	20	C	SM
16	12.19.67	1. 6.68	D	20	C	MN1
17	12.19.67	1. 1.68	D	20	C	MN2
18	1.16.68	2.14.68	D	20	C	MN3
19a	1.23.68	2. 9.68	D	20	C	MN3
b	2.10.68	3. 7.68	D	20	C	MN4
c	3. 8.68	3.13.68	D	20	C	MN3
20	1.23.68	4. 1.68	N	20	C & V	SM
21	2. 7.68	4. 1.68	N	20	C	SM
22	3.18.68	3.29.68	D	20	C	MN3
22Aa	2.14.68	3. 7.68	D	20	C	MN4
22Ab	3. 8.68	4. 1.68	D	20	C & V	MN3
23	4. 3.68	5. 9.68	N1	20	C	SM
23	4. 3.68	5. 9.68	D1	20	C	SM
23	4. 3.68	5. 9.68	N2	20	C	-
23	4. 3.68	5. 9.68	D2	20	C	SM
24	5.10.68	5.28.68	N1	20	V	SM
24	5.10.68	5.28.68	D1	20	V	SM

Table 3 (continued)

Test No.	Dated		Type[x] of test	Temp °C	Type[y] of flow	Feed[z] solution
	Start	End				
24	5.10.68	5.28.68	N2	20	V	-
24	5.10.68	5.28.68	D2	20	V	SM
25a	5.29.68	8. 8.68	N	20	V	SM
			D	20	V	SM
25b	8. 9.68	8.18.68	N	20	V	SM
			D	20	V	ML1
25c	8.19.68	9.24.68	N	20	V	SM
			D	20	V	L1
26a	9.26.68	11. 7.68	N	20	V	SM
			D	20	V	L1
26b	11. 8.68	12.18.68	N	15	V	SM
			D	15	V	L1
27a	12. 2.68	2.12.69	N	20	V	SM
			D	20	V	L1
27b	2.13.68	3.14.69	N	10	V	SM
			D	10	V	L1
27c	3.15.69	4. 4.69	N	10	V	SM
			D	10	V	L1
27d	4. 5.69	6.11.69	N	10	V	SM
			D	10	V	L1
28a	6.13.69	8. 3.69	D	10	C	L2
28b	8. 4.69	8.19.69	D	10	C	L3

[x] Type of Test:

N - Nitrification; D - Denitrification
N & D - Nitrification and Denitrification operated in series

[y] Type of Flow:

C - Constant Flow; V - Variable Flow

[z] Feed solution:

SM - Standard Milk Solution as described in Table 2
MN - 120 mg/l milk solids; 120 mg/l $NaNO_3$
MN1 - 112 mg/l " 151 mg/l $NaNO_3$
MN2 - 56 mg/l " 151 mg/l $NaNO_3$
MN3 - 120 mg/l " 129 mg/l "
MN4 - 120 mg/l " 155 mg/l "
MN5 - 240 mg/l " 257 mg/l "
ML1 - 120 mg/l " 0.16 ml/l or 127 mg/l methanol
L1 - 0.32 ml/l or 253 mg/l methanol
L2 - Effluent from a nitrification plant plus L1
L3 - " " " " " 0.25 ml/l or 199 mg/l methanol

Table 4. Reactor Test Operational Data

Test	Reaction Tank*				Settling Tank		
	Vol	DT	Loading		Vol	DT	SSR
No.	l	hrs	BOD/MLVSS	SA	l	hrs	gpd/sf
1	5.0	4.2	0.34	3.3	2.3	1.9	362
2a	5.0	4.2	0.49	2.2	2.3	1.9	358
2b	5.0	4.1	0.47	2.5	2.3	1.8	366
3a	5.0	4.1	0.70	1.6	2.3	1.8	366
3b	5.0	4.2	0.73	1.6	2.3	1.9	359
3c	5.0	4.4	0.72	1.7	2.3	2.0	344
4	5.0	4.4	1.32	0.8	2.3	2.0	342
5	5.0	6.4	0.26	4.6	2.3	2.9	237
6	No Data Analyzed						
7	5.0	4.0	0.34	3.2	2.3	1.8	377
8	5.0	4.0	0.29	3.8	2.3	1.8	375
9	2.3	2.0	1.42	-	2.3	2.0	358
10	No Data Analyzed						
11	No Data Analyzed						
12	5.0	5.2	0.17	6.3	2.3	2.3	287
13a	5.0	6.4	0.16	6.9	2.3	2.9	237
13b	5.0	6.5	0.18	6.0	2.3	2.9	233
14	5.0	4.5	0.31	3.5	2.3	2.0	233
15	No Data Analyzed						
16	5.0	4.6	0.20	5.1	2.3	2.1	326
17	5.0	4.8	0.08	12.6	2.3	2.1	315
18	5.0	6.0	0.15	8.9	2.3	2.7	250
19a	5.0	8.3	0.20	6.7	2.3	3.8	180
19b	5.0	4.7	0.20	5.9	2.3	2.1	322
19c	5.0	4.7	0.15	7.6	2.3	2.1	323
20	5.0	7.2	0.17	7.4	2.3	3.2	208
21	5.0	7.4	0.21	5.8	2.3	3.3	202
22Aa	2.3	2.3	0.34	3.6	2.3	2.3	295
22Ab	2.3	2.6	0.31	3.7	2.3	2.6	265
23:N1	7.3	8.2	0.20	5.9	5.0	5.7	117
23:D1	5.0	4.0	0.26	6.0	5.0	4.0	167
23:N2	2.3	1.8	-	-	2.3	1.8	377
23:D2	2.3	1.6	0.14	8.3	2.3	1.6	410
24:N1	7.3	10.6	0.13	9.2	5.0	7.3	92
24:D1	5.0	5.1	0.19	5.8	5.0	5.1	136
24:N2	2.3	2.2	-	-	2.3	2.2	307
24:D2	2.3	1.8	-	-	2.3	1.8	350
25a:N	7.3	8.1	0.12	10.5	5.0	5.5	121
D	5.0	3.9	0.32	3.5	5.0	3.9	169
25b:N	7.3	8.9	0.18	6.5	5.0	6.1	110
D	5.0	4.2	0.25	4.7	5.0	4.2	157

* For Nitrification Tests: Aeration Tank

* For Denitrification Tests: Tank Mixed Without Air

Table 4. Reactor Test Operational Data

		Reaction Tank*			Settling Tank		
Test	Vol	DT	Loading		Vol	DT	SSR
No.	l	hrs	BOD/MLVSS	SA	l	hrs	gpd/sf
25c:N	7.3	8.2	0.22	5.2	5.0	5.6	119
D	5.0	4.1	0.32	3.6	5.0	4.1	161
26a:N	7.3	7.6	0.14	7.9	5.0	5.2	124
D	5.0	3.4	1.45	0.8	5.0	3.4	191
26b:N	7.3	8.8	0.13	8.7	5.0	6.1	110
D	5.0	4.0	0.66	1.6	5.0	4.0	168
27a:N	7.3	7.5	0.21	5.5	5.0	5.2	125
D	5.0	3.3	0.86	1.5	5.0	3.3	193
27b:N	7.3	8.6	0.24	4.8	5.0	5.9	109
D	5.0	3.8	0.81	1.4	5.0	3.8	170
27c:N	7.3	17.1	0.15	7.7	5.0	11.8	44
D	5.0	7.5	0.16	6.8	5.0	7.5	87
27d:N	7.3	7.5	0.32	3.6	5.0	5.2	125
D	5.0	3.4	0.49	2.3	5.0	3.4	191
28a:D	5	3.0	0.27	4.0	5.0	3.0	224
28b:D	5	2.7	0.43	2.4	5.0	2.7	244

* For Nitrification Tests: Aeration Tank

* For Denitrification Tests: Tank Mixed Without Air

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 1: July 10-29, 1967. N, C, 20°											
No. of Obs.	20	15	15	1	2	--	12	2	13	13	3
Mean	20.1	3755	3395	6.2	0.3		14.4	6.3	99	77	1.3
Min.	17.7	3050	2840		0.0		11.8	6.0	24	22	1.3
Max.	23.3	4720	4330		0.6		17.5	6.5	260	210	1.3
Test 2a: July 10- Aug. 8, 1967. N, C, 20°											
No. of Obs.	28	25	25	1	2	--	22	3	21	21	3
Mean	19.8	2526	2336	1.0	0.7		7.7	6.5	100	80	1.1
Min.	16.2	1910	1630		0.0		0.7	6.2	15	12	1.0
Max.	21.9	3130	2820		1.4		16.0	6.7	220	170	1.2
Test 2b: Aug. 24 - Sept. 8, 1967. N, C, 20°											
No. of Obs.	15	16	16	2	2	2	16	3	15	15	3
Mean	20.3	2935	2470	1.3	9.9	0.3	8.6	6.2	109	90	0.7
Min.	18.5	2220	1930	0.4	6.2	0.0	0.2	5.5	20	0	0.1
Max.	22.8	4160	3600	2.2	13.6	0.5	20.0	7.2	500	455	1.7
Test 3a: July 15 - Aug. 7, 1967. N, C, 20°											
No. of Obs.	19	15	15	--	--	--	19	3	12	12	--
Mean	20.3	1800	1655				5.8	6.6	193	166	
Min.	11.5	960	950				0.2	5.2	30	30	
Max.	26.2	3070	2870				16.5	6.7	396	396	
Test 3b: Aug. 24 - Sept. 3, 1967. N, C, 20°											
No. of Obs.	10	11	11	2	2	2	11	3	10	10	2
Mean	19.9	1850	1555	2.6	8.1	0.3	3.7	6.8	134	117	0.2
Min.	18.7	1240	1060	2.0	2.1	0.0	0.1	5.9	70	50	0.1
Max.	21.4	2340	1980	3.2	14.0	0.7	7.2	7.4	270	225	0.4

Table 5 2

REACTOR TEST ANALYTICAL DATA

Test No.	Rate of Flow ml/min	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
		SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 3c: Sept. 4-8, 1967 . N, C, 20°											
No. of Obs.	4	5	5	1	--	--	4	1	4	4	1
Mean	19.1	1852	1526	2.0			10.0	7.2	159	134	0.4
Min.	18.0	1510	1270				8.2		70	30	
Max.	20.0	2120	1800				11.7		295	245	
Test 4: July 27 - Aug. 11, 1967 . N, C, 20°											
No. of Obs.	10	9	8	--	2	2	13	3	6	5	--
Mean	19.0	912	819		13.9	0.0	1.4	5.2	120	100	
Min.	15.6	640	580		13.6	0.0	0.1	4.2	70	45	
Max.	21.7	1220	1050		14.2	0.0	5.3	6.2	212	188	
Test 5: Sept. 12 -Sept. 22, 1967. N, C, 20°											
No. of Obs.	9	10	10	--	--	--	9	--	9	10	--
Mean	13.1	3430	2920				15.5		139	102	
Min.	11.8	2780	2310				12.4		10	10	
Max.	15.1	4000	3370				19.2		475	410	
Test 6: Sept. 22 - Oct. 13, 1967 No Data Analyzed											
Test 7: Oct. 13 - 25, 1967. N, C, 20°											
No. of Obs.	12	10	10	--	--	--	10	1	7	7	--
Mean	20.9	3837	3475				18.6	4.6	40	34	
Min.	19.3	3330	2990				16.0		16	16	
Max.	22.4	4370	4090				22.0		86	64	
Test 8: Oct. 13 - 25, 1967. N, C, 20°											
No. of Obs.	12	10	10	--	--	--	10	1	9	9	--
Mean	20.8	4525	4049				18.5	5.0	35	29	
Min.	17.9	4110	3780				16.0		4	4	
Max	24.5	4870	4340				22.0		116	92	

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 9: Oct. 25-30, 1967*. D, C, 20°											
No. of Obs.	5	1	1	1	1	1	4	--	--	--	1
Mean	19.3	880	760	5.6	3.4	0.1	0.2	28 (BOD)			0.9
Min.	14.6										
Max.	22.7										
Test 10: Oct. 27-29, 1967 No Data Analyzed											
Test 11: Oct. 27-29, 1967 No Data Analyzed											
Test 12: Nov. 14-22, 1967 . D, C, 20°											
No. of Obs.	6	5	4	--	--	--	9	--	8	7	--
Mean	16.0	2630	2385				0.3		44	35	
Min.	14.9	2300	2040				0.1		16	16	
Max.	16.5	3100	2910				1.7		84	76	
Test 13a: Nov. 14-30, 1967. N, C, 20°											
No. of Obs.	13	13	13	--	--	--	13	--	13	12	--
Mean	13.1	5165	4710				18.4		47	37	
Min.	11.7	4500	4100				8.0		4	4	
Max.	14.5	6450	6040				22.3		116	96	
Test 13b: Nov. 30-Dec. 11, 1967. N, V, 20°											
No. of Obs.	10	10	10	--	--	--	10	--	9	9	--
Mean	12.9	4418	4030				18.3		41	37	
Min.	9.7	3390	3030				13.5		30	30	
Max.	14.8	5080	4620				22.5		58	48	
Test 14: Dec. 5-14, 1967. D, C, 20°											
No. of Obs.	9	1	1	--	--	--	8	--	9	9	--
Mean	18.5	3400	3000				0.1		36	33	
Min.	13.7						0.1		54	50	
Max.	20.5						0.2		16	16	

*All effluent analyses on 10/30/67

Table 5 -1

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 15: Dec. 18, 1967 - Jan. 1, 1968 No Data Analyzed											
Test 16: Dec. 19, 1967 - Jan. 6, 1968 . D, C, 20°											
No. of Obs.	15	2	2				4				
Mean	18.1	2400	2220				4.5				
Min.	14.2	1390	1270				3.4				
Max.	19.6	3410	3170				5.6				
Test 17: Dec. 19, 1967 - Jan. 1, 1968. D, C, 20°											
No. of Obs.	12	2	2				8				
Mean	17.5	2640	2430				15.4				
Min.	13.2	1870	1690				9.0				
Max.	20.0	3410	3170				20.0				
Test 18: Jan. 25 - Feb. 14, 1968. D, C, 20°											
No. of Obs.	15	11	11	1	1	1	13	1	11	11	1
Mean	13.8	3230	2350	7.8	4.1	.01	0.3	16 (BOD)	79	64	1.3
Min.	11.6	1610	1130				0.0	52 (COD)	12	12	0.6 (OP)
Max.	17.3	5810	3980				1.4		240	230	
Test 19a: Jan. 23 - Feb. 9, 1968. D, C, 20°											
No. of Obs.	13	10	10		1	1	11		8	8	
Mean	10.0	1751	1335		2.6	0.03	0.3		81	64	
Min.	7.8	1230	950				0.1		32	16	
Max.	11.5	2840	2060				2.6		560	470	
Test 19b: Feb. 10 - Mar. 7, 1968. D, C, 20°											
No. of Obs.	25	16	16				17	1	13	13	
Mean	17.9	2750	2350				0.6	129 (COD)	51	45	
Min.	13.2	1840	1590				0.0		4	4	
Max.	23.2	3670	3170				2.3		120	112	

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 19c: Mar. 8 - Mar. 13, 1968 . D, C, 20°											
No. of Obs.	6	3	3				3		3	3	
Mean	17.9	3550	3030				0.1		71	45	
Min.	17.3	3110	2660				0.1		28	16	
Max.	18.5	4170	3510				0.2		96	84	
Test 20: Feb. 14 - April 1, 1968 . N, V, 20°											
No. of Obs.	40	25	25	1			21		22	22	
Mean	11.6	4885	3800	1.2			20.0		50	37	
Min.	10.2	3860	2920				16.5		4	0	
Max.	17.2	6340	5050				25.8		124	108	
Test 21: Feb. 13 - April 1, 1968 . N, C, 20°											
No. of Obs.	45	25	25				22		21	21	1
Mean	11.2	3700	3050				20.6		52	38	1.4
Min.	7.3	2000	1610				5.5		0	0	
Max.	18.0	6660	5830				29		536	420	
Test 22: March 18 - March 29, 1968 No Data Analyzed											
Test 22Aa: Feb. 14 - March 5, 1968. D, C, 20°											
No. of Obs.	20	12	12				13		11	11	
Mean	16.3	3390	2810				0.6		45	40	
Min.	10.6	1740	1480				0.1		0	0	
Max.	20.5	4700	4100				1.2		76	76	
Test 22Ab: March 12 - April 1, 1968. D, V, 20°											
No. of Obs.	13	8	8				3	1	4	4	
Mean	14.7	3165	2800				0.2	39 (COD)	52	44	
Min.	14.0	2750	2300				0.1		44	24	
Max.	15.7	3590	3200				0.3		64	44	

Table 5

REACTOR TEST ANALYTICAL DATA

Test No.	Rate of Flow ml/min	Mixed Liquor mg/l SS	Mixed Liquor mg/l VSS	Effluent Concentrations, mg/l TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 23: April 3 - May 9, 1968 . C, 20°											
N_1:											
No. of Obs.	16	16	16				28		3	3	
Mean	14.7	3440	2920				20.6		13	13	
Min.	10.5	1520	1330				14.0		7	7	
Max.	24.0	4720	4130				24.5		16	16	
D_1:											
No. of Obs.	29	16	16				24		4	4	
Mean	20.6	1440	1290				0.6		72	57	
Min.	--	700	620				0.1		25	22	
Max.	--	2050	1920				2.4		128	76	
N_2:											
No. of Obs.	29	16	16				28		5	5	
Mean	20.6	2300	1990				7.8		32	21	
Min.	--	1310	1100				2.8		10	9	
Max.	--	2660	2260				15.6		52	40	
(April 28 - May 9, 1968)											
D_2:											
No. of Obs.	8	9	9				11		1	1	
Mean	24.0	350	310				0.6		29	23	
Min.	--	140	90				0.1				
Max	--	880	800				2.4				

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l								
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	COD	SS	VSS	TP	pH
Test 23: May 3, 1968 . C, 20°												
N_1:												
No. of Obs.	1	1	1	1	1	1	1	1	1	1	1	1
	13.9	3120	2720	2.8	1.8	0.7	17.3	40	7	7	1.8	7.7
D_1:												
No. of Obs.	1	1	1	1	1	1	1	1	1	1	1	1
	20.3	1700	1590	8.8	5.4	0.0	0.1	57	25	23	1.8	7.8
N_2:												
No. of Obs.	1	1	1	1	1	1	1	1	1	1	1	1
	20.3	2570	2220	2.9	0.5	0.0	6.3	35	10	9	1.7	8.0
D_2:												
No. of Obs.	1	1	1	1	1	1	1	1	1	1	1	1
	24.0	400	380	6.5	3.1	0.1	0.1	56	29	23	1.8	7.8
Test 24: May 10 - May 28, 1968. V, 20°												
N_1:												
No. of Obs.	7	11	11				10					
Mean	11.4	4140	3500				22.9					
Min.	9.7	3400	2784				17.3					
Max.	13.2	5200	4263				25.0					
D_1:												
No. of Obs.	5	11	11				8					
Mean	17.0	1830	1630				0.4					
Min.	--	1580	1440				0.1					
Max.	--	2100	1840				0.7					
N_2:												
No. of Obs.	5	11	11				10					
Mean	17.0	1760	1460				8.5					
Min.	--	1280	1000				6.3					
Max.	--	2400	2020				11.0					
D_2:												
No. of Obs.	5	--	--				9					
Mean	19.5	(Wash					2.3					
Min.	--		Out)				0.1					
Max.	--	--	--				4.3					

Table 5 8

REACTOR TEST ANALYTICAL DATA

Test No.	Rate of Flow ml/min	Mixed Liquor mg/l SS	 VSS	Effluent Concentrations, mg/l TKN	 NH_3-N	 NO_2-N	 NO_3-N	 DO	 SS	 VSS	 TP
Test 25a: June 10, 1968 - Aug. 8, 1968. V, 20°											
N:											
No. of Obs.	57	38	37						32	27	
Mean	15.1	4730	3900				(20.0)		20	15	
Min.	11.0	3200	2680						4	2	
Max.	21.0	6420	5410						45	35	
D:											
No. of Obs.	56	38	35		19	2	31	1	31	28	
Mean	21.3	1220	1130		4.9	0.0	0.3	30	64	49	
Min.	19.3	400	520		3.8	0.0	0.1	(COD)	25	10	
Max.	26.4	1900	1680		8.8	0.1	0.7		140	128	
Test 25b: August 9, 1968 - August 18, 1968 . V, 20°											
N:											
No. of Obs.	10	5	5						5	5	
Mean	13.7	3500	2980				(20.0)		40	30	
Min.	12.1	2920	2420						10	8	
Max.	16.2	3890	3280						70	57	
D:											
No. of Obs.	10	5	5		6		6		5	5	
Mean	19.7	1584	1362		3.4		0.3		45	35	
Min.	18.8	1070	880		1.8		0.1		27	25	
Max.	20.4	2220	1870		4.9		0.5		65	56	
Test 25c: August 19, 1968 - Sept. 13, 1968 . V, 20°											
N:											
No. of Obs.	24	16	16						12	11	
Mean	14.9	3130	2715				(19.5)		25	20	
Min,	12.1	2360	2080						6	6	
Max.	16.4	3590	3160						61	50	
D:											
No. of Obs.	24	16	16		13		18		15	13	
Mean	20.2	1150	1000		0.7		0.2		45	38	
Min.	18.5	380	320		0.2		0.1		15	14	
Max.	21.9	2670	2330		1.3		0.4		68	54	

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 25a: August 6, 1968 (Supplementary Data). V, 20°											
D	14.2 (20.5)	830	790	9.6	4.9	0.1	0.3	29 (BOD) 63 (COD)	44	--	2.1
Test 25c: Sept. 5, 1968 (Supplementary Data). V, 20°											
N	14.4	3160	2720	4.9	0.1	0.0	19.5	--	20	17	--
D	20.3	700	580	4.5	0.8	0.0	0.1	27 (BOD) 68 (COD)	38	34	1.4
Test 26a: Oct. 27 - Nov. 7, 1968. V, 20°											
N:											
No. of Obs.	11	4	4		6		6		4	4	
Mean	16.0	4970	4350		0.6		23.6		24	20	
Min.	14.1	4740	4080		0.4		21.5		11	10	
Max.	17.7	5530	4820		0.8		26.5		41	37	
D:											
No. of Obs.	11	4	4		4		6		4	4	
Mean	24.6	390	360		1.4		0.2		17	16	
Min.	22.4	250	210		1.1		0.0		12	9	
Max.	26.8	560	500		2.0		0.6		22	20	
Test 26b: Nov. 14 - Dec. 3, 1968. V, 15°											
N:											
No. of Obs.	17	5	5		4		5		5	5	
Mean	13.7	4690	4180		0.4		20.2		34	19	
Min.	11.4	3620	3360		0.3		16.0		14	10	
Max.	15.6	5360	4810		0.4		24.0		60	54	
D:											
No. of Obs.	17	5	5		5		5		5	5	
Mean	22.2	820	770		1.1		0.3		18	15	
Min.	20.4	700	590		0.1		0.1		7	0	
Max.	23.8	1000	1000		1.8		0.6		23	22	

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 27a: Jan. 13 - Feb. 12, 1969. V, 20°											
N:											
No. of Obs.	29	15	14		17		18		8	4	
Mean	16.1	3480	3020		0.3		16.1		12	8	
Min.	13.2	2820	2410		0.0		12.4		2	4	
Max.	18.4	4050	3880		0.9		21.4		23	13	
D:											
No. of Obs.	31	13	11	2	14		18		13	11	
Mean	25.2	830	640	2.5	1.0		0.1		22	20	
Min.	19.5	410	340	2.0	0.6		0.0		10	12	
Max.	34.5	1710	1390	3.0	1.6		0.3		33	29	
Test 27b: March 3 - March 14, 1969. V, 10°											
N:											
No. of Obs.	11	4	4		5		5		4	4	
Mean	14.1	2640	2350		0.8		14.8		10	7	
Min.	13.1	2280	2090		0.4		13.6		7	4	
Max.	15.7	2840	2500		1.8		15.8		13	12	
D:											
No. of Obs.	11	4	4		5		5		4	4	
Mean	21.3	600	540		1.0		0.3		18	15	
Min.	19.7	520	430		0.8		0.1		11	9	
Max.	25.9	700	620		1.6		0.6		27	24	
Test 27c: March 15 - April 4, 1969. V, 10°											
N:											
No. of Obs.	20	3	4		6		8		2	1	
Mean	7.1	2140	1825		0.7		16.6		10	8	
Min.	5.7	1550	1390		0.3		14.4		9		
Max.	9.3	2570	2050		1.3		19.8		12		
D:											
No. of Obs.	19	2	2		9		9		2	1	
Mean	11.0	1600	1440		0.7		0.1		12	12	
Min.	6.3	1560	1390		0.4		0.0		12		
Max.	12.6	1640	1490		1.2		0.2		13		

Table 5

REACTOR TEST ANALYTICAL DATA

Test	Rate of Flow	Mixed Liquor mg/l		Effluent Concentrations, mg/l							
No.	ml/min	SS	VSS	TKN	NH_3-N	NO_2-N	NO_3-N	DO	SS	VSS	TP
Test 27d: April 17 - May 14, 1969. V, 10°											
N:											
No. of Obs.	26	3	3		5		5		2	2	
Mean	16.2	2300	1980		0.7		14.3		8	7	
Min.	13.0	1990	1740		0.4		10.8		4	3	
Max.	18.3	2540	2140		1.2		16.6		12	12	
D:											
No. of Obs.	24	3	3		5		5		2	1	
Mean	24.8	1220	1065		0.9		0.2		11	15	
Min.	20.3	665	585		0.8		0.1		6		
Max.	27.9	1840	1590		1.1		0.2		16		
Test 28a: June 13 - June 22, 1969. C, 10°											
(N:) *											
No. of Obs.	9				5		6				
Mean	19.4				0.5		21.1				
Min.	12.6				0.2		19.8				
Max.	22.7				0.9		22.2				
D:											
No. of Obs.	9	2	2		5		6				
Mean	28.0	2275	1965		0.5		0.3				
Min.	19.7	1960	1710		0.2		0.2				
Max.	32.0	2590	2220		1.2		0.5				
Test 28b: August 4 - August 18, 1969. C, 10°											
(N:)*											
No. of Obs.	15				11		11				
Mean	21.5				0.5		23.6				
Min.	16.6				0.4		22.4				
Max.	23.6				0.5		24.2				
D:											
No. of Obs.	15	11	11		4		11				
Mean	30.5	1010	863		0.7		0.3				
Min.	24.9	550	470		0.3		0.3				
Max.	33.3	1390	1113		1.3		0.4				

* See discussion section for significance of these data.

D. Experimental Results of Reaction Tests

1. General Test Conditions

A list of the reaction tests including the period of operation, type of test, temperature, and type of flow is presented in Table 3, Listing of Reactor Tests. The tests have been numbered chronologically and it is apparent that, at times, two or more tests were conducted simultaneously. For the Type of Test, the N or D designates nitrification or denitrificqtion respectively. For the Type of Flow, C represents a constant rate of flow while V is for variable flow conditions. Feed Solution designations described at the bottom of the table represent concentrations of various substances mixed with dechlorinated City of Minneapolis tap water for use as raw feed solutions for the reactors.

Operational data from all of the reactor tests are shown in Table 4. The Reaction Tank is the aeration tank when used with a nitrification test and is a mixed anaerobic tank with the denitrification process. The reaction tank volume is given in liters, detention time (DT) in hours, and loading in terms of either of two ratios. The ratio, BOD/MLVSS, is actually the pounds of 5-day 20°C BOD of the raw feed added to the reactor per day divided by the pounds of mixed liquor volatile suspended solids in the system. The term SA is a similar ratio but in the weight of mixed liquor suspended solids in the system over the weight of 5-day 20°C BOD fed per day with the raw feed. The settling tank operational data are given as the tank volume in liters, the detention time (DT) in hours, and the surface settling rate (SSR) as gallons per day per square foot. This latter unit is found by dividing the rate of flow by the surface area of the tank.

Included in Table 5, Reactor Test Analytical Data, are flow data, mixed liquor total and volatile suspended solids data, and the effluent analysis data. Effluent concentrations are given as follows:

TKN: total Kjeldahl nitrogen as N

NH_3-N: ammonia nitrogen as N

NO_2-N: nitrite nitrogen as N

NO_3-N: nitrate nitrogen as N

DO: dissolved oxygen

SS: suspended solids

VSS: volatile suspended solids

TP: total phosphorus as P

Some effluent BOD (5-day, 20°C) and COD data also have been included in the DO column and are specifically so designated. Some ortho-phosphate concentrations are shown as OP in the TP column. Because of operational difficulties encountered during the tests, the data were analyzed only when it was considered that equilibrium conditions had been reached. Consequently the time period of each test as shown in Table 3 and the dates shown in Table 5 may not be the same. The dates shown in Table 5 represent the periods over which the listed data were collected. The letters and numbers following the dates designate the temperature of operation in degrees centigrade, the pattern of flow as being constant (C) or variable (V), and whether the objective of the test was to achieve nitrification (N) or denitrification (D).

Additional denitrification data are presented in Table 6, Reactor Denitrification Test Data. For each denitrification test the influent nitrate concentration is given and the carbon source (BOD) is given as either milk solids (M) or methanol (L). Three characteristics of the reactor tank operation are presented: the organic loading rate (For BOD/MLVSS) as listed previously in Table 4; the nitrate reduction rate as mg nitrate-N removed per hour per g of MLSS in the reaction tank (mg N/gMLSS/hr); and the ratio of BOD_5 in the carbon source added to the reaction tank to the nitrate-N

Table 6. Reactor Denitrification Test Data

Test No.	Feed Nitrate mg/l-N	Carbon* source	Reaction Tank			
			Loading BOD/MLVSS F	Nitrate reduction rate mg N/g MLSS/hr R	Ratio:** BOD_5/Nitrate-N	
					BOD/NA Applied	BOD/N Removed
9	19.9	M	1.42	11.2	4.22	4.26
12	19.9	M	0.17	1.4	4.22	4.28
14	42.3	M	0.31	2.8	4.11	4.12
16	24.9	M	0.20	1.5	3.13	3.82
17	24.9	M	0.08	0.3	1.45	3.79
18	21.3	M	0.15	1.1	3.94	4.01
19a	21.3	M	0.20	1.5	3.94	4.01
19b	25.5	M	0.20	2.0	3.29	3.37
19c	21.3	M	0.15	1.3	3.94	3.96
22Aa	25.5	M	0.34	3.1	3.29	3.37
22Ab	21.3	M	0.31	2.6	3.94	3.98
23:D_1	20.6	M	0.26	2.4	3.41	3.52
23:D_2	7.8	M	0.14	1.1	3.25	3.52
24:D_1	22.9	M	0.19	1.7	3.82	3.90
25a	(20.0)	M	0.32	2.8	3.80	3.86
25a	20.0	M	0.46	4.4	3.73	3.78
25b	(20.0)	ML	0.25	2.0	4.02	4.08
25c	(19.5)	L	0.41	2.9	3.50	3.54
25c	19.5	L	0.43	5.0	3.85	3.97
26a	23.6	L	1.45	11.3	4.39	4.52
26b	20.2	L	0.66	4.0	5.96	6.07
27a	16.1	L	0.86	3.7	6.78	6.82
27b	14.8	L	0.81	4.1	6.66	6.80
27c	16.6	L	0.16	0.9	6.35	6.39
27d	14.3	L	0.49	1.4	11.60	11.80
28a	21.1	L	0.27	2.1	4.40	4.46
28b	23.6	L	0.43	6.0	2.58	2.59

* Carbon source: M Milk solids
L Methanol

** BOD_5 corrected to that available to the nitrates after depletion of D.O.

applied (BOD/NA) or nitrate-N removed (BOD/N). It should be noted that the BOD_5 in the BOD/N ratio computations has been corrected to that available to the nitrates after deducting an amount required to deoxygenate the incoming flows. The rates of nitrate reduction and organic loading rates are plotted as Figure 10.

2. Tests 1, 2, 3 and 4

These tests were conducted simultaneously for the purpose of determining the concentration of mixed liquor suspended solids (MLSS) necessary to maintain a nitrifying activated sludge system when the aeration time was approximately 4 hours. The test data and conditions shown in Tables 3, 4 and 5 show that the hydraulic loadings for each system were approximately the same. The only essential difference in the systems was in the concentrations of MLSS in each of the reactors to give varying reaction tank loading parameters.

It was difficult to control the solids in these tests because of sludge bulking, and these poor sludge settling conditions were indicative of similar operating problems which would be encountered throughout the reactor test program.

Of these four tests only in Test 1 was there any significant degree of nitrification. Downing and Hopwood(34) showed the minimum residence time (t_R) of the mixed liquor to achieve nitrification as:

$$t_R = \frac{\Delta S}{kS}$$

ΔS = change in concentration of MLSS

S = concentration of MLSS

k = growth rate constant of nitrosomonas.

Johnson and Schroepfer(2) indicated a loading rate of 0.35 lbs/day/lb MLSS should not be exceeded to obtain continuous nitrification. Only in Test 1 was the loading rate within this limit and the computed minimum aeration time was

4.1 hrs compared to an actual 4.2 hrs. It was observed that the nitrate concentration in Test 1 was gradually decreasing so that the fact that operation was very close to the limiting conditions was borne out by theoretical and experimental results.

In Tests 2, 3 and 4 the loading rates all exceeded the assumed maximum of 0.35 and the computed minimum aeration times in all cases exceeded the actual operating conditions. The fact that there was any nitrification at all was because the sludge used initially did contain nitrifying bacteria. Again the general observation from these tests is that the minimum essential aeration period and loading rate for nitrification as defined in previous work is in agreement with these results.

3. Tests 5 and 6

These tests were conducted simultaneously using the sludge remaining from Tests 1 and 2 respectively. It was intended to operate each unit with an aeration time of 6 hours and a MLSS concentration of 3000 mg/l. The difference between the two systems was that prior to the start of the tests, the sludge used for Test 6 was chlorinated in an attempt to reduce the sludge bulking.

With the lower loading conditions used in Test 5 compared to the previous tests, nitrification was maintained at a high concentration. Severe bulking again occurred, and the sludge was chlorinated with 75 mg/l residual chlorine on September 22. The result of chlorination was to inhibit the nitrifiers as evidenced by nitrate concentrations near zero shortly thereafter. The sludge volume index of the sludge did not improve immediately but stayed well over 200 for about 10 days, and finally after about 20 days it had decreased to 100. Assuming that the chlorine either killed or prevented further growth of (filamentous) organisms causing the bulking, it could take a number of days to wash out the undesirable cell debris. By assuming a net specific growth rate of the sludge of 0.20 per day, it may be shown that due to wash-out the sludge would contain only 15 to 20 per cent of the original filaments after 10 days. It is conceivable that this lower concentration was sufficient to allow the solids to compact more. After approximately 20 days the nitrate concentration showed an increase indicating that the nitrifiers were not completely destroyed.

The data from Test 6 were not analyzed but it was again shown that chlorination did not completely destroy the nitrifiers, and the sludge volume index did not show improvement until after approximately 15 days of operation. Initially the nitrate concentration was less than 0.5 mg/l and then gradually increased to 14.0 mg/l after 15 days.

4. Tests 7 and 10

Tests 7 and 10 were nitrification tests and an attempt again was made to obtain nitrification at a 4-hour detention time. Sludge from the pilot plant was used and with a mean MLSS concentration of 3837 mg/l the nitrate concentration was kept at an average value of 18.6 mg/l. Again the actual detention time exceeded the computed minimum and the load ratio of 0.30 was less than the prescribed maximum. The test was concluded on October 25.

The sludge from Test 7 was used for Test 10 and the operating conditions were changed to a 6-hour retention time and a MLSS concentration of 2000 mg/l. At the end of Test 7 the sludge volume index (SVI) had gone to 220, and after only 2 days of operation with this sludge it was decided it was too difficult to continue operations and the test was terminated. No data were analyzed from this period.

5. Tests 8 and 11

Test 8 was run in parallel with Test 7 and was a nitrification test differing from Test 7 only in using a higher MLSS concentration. With these lower loadings the effluent nitrate concentration was high. The effluent concentrations were almost exactly the same as for Test 7 where the loading rate was somewhat higher. Throughout this test the SVI was low and the test was terminated on October 26 when a line broke.

The sludge from Test 8 was used for Test 11 and it was intended to use this sludge with a detention time of 4 hours and the MLSS concentration reduced to 3000 mg/l. The test was only operated for two days because of a sudden increase in the SVI. It is not known why the SVI suddenly increased. Although higher loadings often result in high SVI values, it is unlikely that the response would come in only two days of operation.

6. Test 9

This was the first denitrification test and was operated with a sodium nitrate solution together with a dry milk solids carbon source. For unexplainable reasons the mixed liquor solids washed out of the reaction tank and the test had to be terminated after five days.

During the five day period of operation the effluent nitrate concentration decreased gradually to 0.2 mg/l on the day on which the data are reported. As shown in Table 6 the BOD_5/nitrate-N (BOD/N) ratio used was 4.26 and the high sludge loading resulted in a high rate of nitrate reduction.

7. Test 12

This test was a denitrification test similar to Test 9 whereby a mixture of milk solids and sodium nitrate was added to an aerobic mixed reactor. The mixed liquor solids were obtained from a nitrifying activated sludge plant but adapted well to denitrifying conditions after only 2 days of operation. The holding time in the reaction tank was 5.2 hours in contrast to 2.0 hours in Test 9. At this longer holding time the solids did not wash out of the system but there were signs of sludge bulking at the end of the test. The BOD/N ratio was 4.28 and the nitrate reduction rate was low corresponding to the low sludge loading rate.

8. Tests 13a and 13b

Test 13a was a constant flow nitrification test to develop a good sludge to be used in the subsequent variable flow test, Test 13b. The aeration time and MLVSS were kept quite high so that the BOD/MLVSS ratio was only 0.17. As expected, consistent nitrification was achieved.

After 16 days of operation the feed pump was put on a variable flow cycle. The variable flow cycle was approximately as shown in Figure 7 for Test 20. The ratios of maximum to average and minimum to average flow were 1.7 and 0.5 respectively. With the particular conditions used in these tests, the mean nitrate concentration in the daily composite samples was the same as that obtained with constant flow conditions. It would appear that variable flow in this case had no effect, but since there were a number of mechanical equipment problems during the test and sludge bulking near the end of the period, the results were not conclusive.

9. Test 14

During this constant flow denitrification test the ratio of BOD/N was 4.12, and although somewhat less than that used previously, satisfactory denitrification was achieved. Inadvertently the sodium nitrate and milk solids concentrations were made up to essentially twice the intended concentrations which placed a higher load on the sludge in the reactor. The BOD/MLVSS and SA values were 0.31 and 3.5 respectively and very similar to conventional activated sludge. The nitrate reduction rate of the sludge was 2.8 as shown in Table 6.

10. Tests 16 and 17

These tests were denitrification tests using milk solids as a carbon source and sodium nitrate as the nitrate source. Lower ratios of BOD/N were used than in previous tests as shown in Table 6. Although the BOD/N-applied ratios for the two tests (computed using the nitrate N added) differed greatly, the ratios were essentially the same when computed using the nitrate removed. It would appear that the optimum ratio of BOD/N is approximately 3.80 and that the magnitude of nitrate reduction is, therefore, primarily a function of the BOD/N ratio. The effect of a particular sludge loading rate is not to effect a greater or lesser amount of substrate reduction but to determine the effluent quality in terms of some parameter such as BOD_5.

11. Test 18

This was a denitrification test operated at a BOD/N ratio higher than the estimated optimum, and good denitrification was achieved. The effluent obtained in this test was quite turbid as indicated by the SS concentration. BOD and COD data were obtained on one day and it is evident that a good quality effluent was being produced in terms of total BOD_5 and that the soluble BOD_5 would certainly be somewhat less than the 16 mg/l. Complete nitrogen and phosphorus data were also obtained on the same day as the BOD-COD data.

The total of the organic and ammonia nitrogen (TKN) entering the system was 7.0 mg/l while the phosphorus in the feed was 1.2 mg/l. Because of the high effluent solids the TKN of the effluent exceeded that of the influent but the soluble ammonia was 4.1 mg/l. The total phosphorus in the effluent was also high because of the effluent solids but the ortho-phosphate (OP) was 0.6 mg/l. Some loss of influent TKN and TP were evident but where the sum of all forms of nitrogen in the effluent must be low it is evident that a carbon source containing little or no nitrogen is necessary.

12. Tests 19a, 19b, 19c

These three tests were conducted in series with the same sludge and same units. The differences in the tests were in the hydraulic and organic loadings and in the BOD/N ratios used in the feed. Essentially complete denitrification was obtained in all tests.

Tests 19a and 19c were conducted with the same BOD/N ratio and with similar sludge loading rates. The principal difference was in the detention times and mixed liquor solids concentrations in the reactors. It is quite evident that either combination of time and concentration was satisfactory.

Test 19b was operated at a similar sludge loading but at a reduced BOD/N ratio and the denitrification held up very well. Consequently the ratio considered optimum previously (3.8) should be modified to the ratio of 3.4.

In all tests there was a high concentration of SS in the effluent, but it was noted on the log sheets that towards the end of Test 19b the characteristics of the sludge changed suddenly to produce a very clean effluent but a very fluffy sludge.

13. Tests 20 and 21

These two tests were nitrification tests run in parallel. The plants were started at approximately the same time with very similar operating conditions and constant flow rates. After a period of equilibrium operation the unit of Test 20 was put on a variable flow cycle as shown on Figure 7 while the other unit for Test 21 was continued with a constant flow rate. For the variable flow the maximum to average rate was 1.73 and the minimum to average rate was 0.49.

The data shown in Table 5 offer no conclusive evidence of an appreciable difference in nitrification in the two plants. In both plants the effluent solids were quite high but the nitrate concentrations were about the same.

14. Tests 22Aa and 22Ab

The denitrifying sludge from Test 18 was used in these tests. Test 22Aa was conducted at a constant flow and then when the input flow rate was changed to a variable cycle the test period was designated as Test 22Ab. Other operating parameters during the tests were the same except that on March 8, after the end of Test 22Aa and shortly before commencing Test 22Ab, the ratio of BOD/N was changed. It was considered at the time that denitrification was not as complete as it should have been and therefore the ratio was actually increased. The decision to do this was probably a questionable one since the mean value was 0.6 and the mean during Test 22Ab with the higher ratio was only decreased to 0.2. However, the variation during the latter test was less.

An analysis of the data from these tests is significant insofar as the efficiency of denitrification is concerned and in comparing the two tests where Test 22Aa was at a constant flow and Test 22Ab was operated at a variable flow. Denitrification test data are shown in Tables 3, 4, 5 and 6 and overall there seems little difference in the nitrate reduction efficiency in either of the two tests. In both tests the mean effluent nitrate concentration was less than 1.0 mg/l. Satisfactory denitrification was achieved in Test 22Aa at a BOD/N ratio of only 3.4 but only slightly better reduction was achieved in Tests 22Ab at a ratio of 4.0. Under these conditions variable flow seemed to have little effect.

15. Test 23

Test 23 was the first test where nitrification and denitrification plants were operated in series. Actually four plants were operated in series: the first was for nitrification; the second was denitrification using milk solids as the carbon source; the third was for nitrification of the remaining ammonia in the denitrified effluent; and the fourth was for final denitrification using milk solids again as the carbon source. Raw waste flows were added to the first, second, and fourth reactors so that the total flow being processed increased progressively through the plant as shown in Table 5.

As shown in Table 4, the low loading conditions used for the first unit assured reasonably complete nitrification. The usual criterion of a low BOD/MLVS ratio to assure nitrification was not applicable for the third stage since essentially a very low BOD concentration entered the unit. With the low BOD, the growth in the third unit was very low and the effluent solids loss was sufficient to maintain a reasonably constant solids concentration. Solids carryover from the second stage also helped to maintain a sludge mass. A holding time of less than 2 hours was used in the second nitrification stage and the optimum time may have been even less. Denitrification loading conditions are also shown in Table 4 and in Table 6. The long detention time in the first denitrification unit was very likely unnecessary but only 1.6 hours was used for the second denitrification stage. The BOD/N ratios were close to the optimum based on previous experience.

The analytical data shown in Table 5 consists of the usual mean values but also includes a complete set of data for what is considered as an equilibrium situation. The progression of total nitrogen through the plant is also shown in Table 7 where influent concentration in the total influent and effluent flows are shown. The tabulation of mean data are indicative of the overall general performance but the equilibrium test data obtained on May 3 are most significant. The data are summarized in Tables 5 and 7.

Table 7. Equilibrium nitrogen data, Test 23 May 3, 1968
Nitrogen concentration, mg/l N

Reactor No.	N1	D1	N2	D2
Influent	27.0	22.6	8.9	11.7
Effluent	20.8	8.9	9.2	6.7
Raw-waste feed	27.0	7.7	-	3.8
Per cent removal	23	67	66	86

The ammonia-N from reactor N1 was higher than expected and it is certain this could be maintained at less than 1.0 mg/l. Approximately 0.7 mg/l of the effluent N concentration was in the SS.

In the first denitrification stage the total removal by the system was 67 per cent and about 2.5 mg/l^{-N} was present in the effluent SS.

The second stage nitrification unit operated to produce a well nitrified effluent and since it was estimated that the effluent solids accounted for all solids growth there should be essentially no removal through the unit (actually a slight negative removal is shown due to ordinary sampling variations).

The second denitrification stage produced a low nitrate concentration but because of the introduction of raw waste the total effluent N was 6.7 mg/l for an overall removal of 86 per cent. Actually the total soluble N was only about 3.7 mg/l. The effect of the first two stages was to remove 18.1 mg/l N and the remaining two stages removed an additional 2.3 mg/l for a total of 20.3 mg/l.

Phosphorus was affected only slightly through the plant and the effluent COD values were indicative of well stabilized effluents.

16. Test 24

Test 24 was a continuation of Test 23 but with variable flow conditions. Denitrification was accomplished with milk solids as the carbon source as shown in Table 3. Based on the results from Test 20 the expected maximum nitrate concentration from the first reactor was assumed to occur 6 hours prior to the time of maximum flow. Consequently the variable flow cycle of raw waste into the second unit was set such that the maximum flow rate (or maximum carbon load) was set to occur 6 hours prior to the maximum flow into the first reactor. With this arrangement it was expected to match the maximum carbon feed with the maximum nitrate load.

As shown in Table 4 the first stage nitrification had a long detention time, and this was due to the unintentional use of a low setting on the feed pump. This also gave an unnecessarily long detention time in the second unit. The two hour holding times in the last two units were reasonable.

The mean data shown in Table 5 indicate that reasonably good operation was obtained from the first three reactors, but the last reactor gave poor results because of an unexplained tendency to lose the mixed liquor solids in the effluent. In general the system operated reasonably well under variable flow conditions. The problems with the fourth reactor cannot be attributed solely due to the variable flow.

17. Tests 25a, 25b and 25c

These tests were two stage operations, the first stage being a nitrification unit and the second a denitrification plant. Variable flow was used to both units with the maximum flow to the second unit lagging the first by 6 hours. The ratio of maximum to average flow was approximately 1.4 and the ratio of minimum to average was 0.6. As shown in Table 3, the main differences in the tests were in the feed solutions to the denitrification plants. Test 25a used a milk solids solution, Test 25b used a mixture of milk and methanol and in Test 25c only methanol was used. Reasonably long detention times were used as shown in Table 4.

It has been shown in previous tests that with the low loading and variable flow completely nitrified effluents could be expected from the first stage unit. For this reason few samples of the effluent were taken and analysed for nitrates. It was estimated that 19.5-20.0 mg/l nitrate-N was available consistently from the conventional activated sludge plant.

Reasonably good denitrification was achieved in Test 25a as shown in Table 5. Data are shown in Table 5 for the entire test period and also for one day when a complete effluent analysis was obtained. The high ammonia and organic nitrogen contents are due to a combination of a proportionately high effluent solids concentration and the fact that milk solids were being used for the carbon source.

In Test 25b the reduction of milk solids and the partial use of methanol lowered the ammonia in the denitrified effluent. Rates of denitrification and ratios of BOD-/N are shown in Table 6.

Test 25c was conducted using only methanol as the carbon source to the denitrification unit and the data are shown both for the entire test period and on one day, September 5, when a complete effluent analysis was obtained. Complete denitrification was obtained but again the total effluent nitrogen was high due to the organic nitrogen content of the effluent suspended solids. The turbidity of the effluent seems to be a disadvantage of this particular process. Although not evident from the data tables the units were operated through September 24 while recording only a limited amount of data. It was shown, however, that complete denitrification was obtained with mixed liquor solids concentrations as low as 350 mg/l.

18. Tests 26a and 26b

These tests were very similar to Test 25 except that for Test 26b the temperature was reduced from 20°C to 15°C. As shown in Table 3 the standard milk solution was used as the input to the nitrification unit while methanol was used as the carbon source for denitrification. Low load ratios were used for both stages as shown in Table 4 and complete nitrification was obtained in both tests. Variable flow was used as with Test 25.

Excellent denitrification was obtained in both tests and the ammonia nitrogen concentrations were slightly over 1.0 mg/l. Effluent suspended solids from the denitrification units were less than 20 mg/l and although no organic nitrogens were determined the concentrations very likely were less than 2 mg/l. Insofar as denitrification is concerned complete denitrification was obtained at the temperature of 15°C. Unfortunately too high a ratio of BOD/N was used to consider defining any optimum conditions.

19. Tests 27a, 27b, 27c and 27d

These four tests were two stage operations with nitrification followed by denitrification. Test 27a was conducted at 20°C but the others were at 10°C. All were conducted with variable flow as described previously. The main differences between Tests 27b, 27c and 27d were in the rates of flow. Sludge bulking encountered in the nitrification unit required lowering the flow rates to somewhat unrealistic levels to provide very long detention times as shown in Table 4, particularly for Test 27c.

The data presented in Table 5 shows that reasonably complete nitrification was obtained from each of the first stage units, and the ammonia concentrations were generally less than 1.0 mg/l. Although the nitrate concentrations were lower than in previous tests there was no corresponding increase in the ammonia. The lower nitrate levels were probably due to decreases in the endogenous metabolism at lower temperatures resulting in less release of nitrogen to the solution to be converted to nitrates.

Denitrification was essentially complete in all tests and again the ammonia concentrations were usually less than 1.0 mg/l. As shown in Table 6, the BOD/N ratios were too high and undoubtedly unoxidized methanol was leaving in the effluent. It was demonstrated previously that methanol may be used much more efficiently than used in these tests.

20. Tests 28a and 28b

In view of the sludge bulking problems encountered in operating a small nitrification unit in series with the denitrification tank it was decided to use effluent from the larger "pilot plant" as the source of nitrates. Although a solution of sodium nitrate could have been used it was considered a bit more realistic to have an actual effluent. These tests were conducted at constant flow and at 10°C using methanol as the carbon source.

It is evident from the data in Tables 5 and 6 that satisfactory denitrification was obtained in 3 hours or less. In Test 28a a rather high BOD/N ratio was used compared to that used in Test 28b. A significantly low BOD/N ratio of 2.58 was used in Test 28b while the corresponding ratio used by Barth(7) was 3.3. Since the work was not confirmed in further tests it is not certain that this low ratio is a completely reliable figure. If it does prove reliable it is even more significant because it was obtained at a temperature of 10°C.

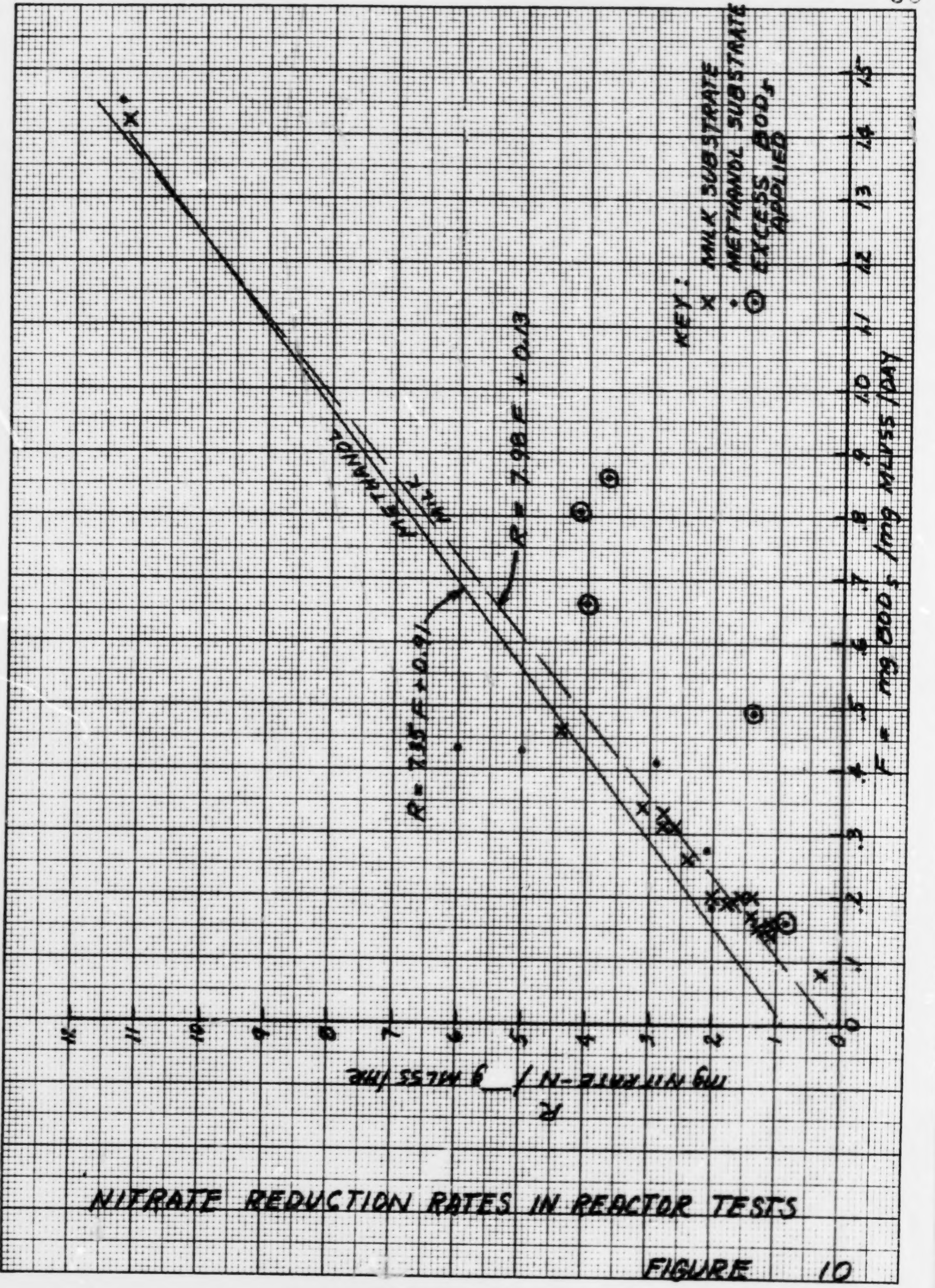
21. Discussion of Reactor Test Results

a. Nitrification

Although the investigation of nitrification was not the primary goal of the research some conclusions may be made from the data obtained. The requirements established previously by Downing, Painter, and Knowles(14) and Johnson and Schroepfer(2) for obtaining nitrification in the activated sludge process were found to be sufficient. It was observed in two tests that continuous nitrification was maintained at 10°C when the aeration tanks were operated at retention times of 7.3 hours and loading rates (BOD/MLVSS) of 0.24-0.32. With aeration tank holding times of 7.0-7.5 hours there was little difference in the degree of nitrification whether the flow was held at a constant rate or varied over a 24-hour period. When chlorine was added in an attempt to control the settleability of the sludge the effect was that settleability improved after about 10 days and nitrification ceased for about 20 days. Apparently the nitrifying bacteria were not completely destroyed since the nitrate concentration showed an increase after 20 days.

b. Denitrification

An aerobic activated sludge was found to require at least 2 days to adapt to anaerobic conditions and be capable of reducing nitrates at a reasonably high rate. Reactor detention times as low as 2.5 hours accomplished rapid denitrification providing sufficient mixed liquor solids were present. The rate and extent of denitrification was found to be a function of both the BOD/MLVSS ratio and the BOD/N ratio. A BOD/MLVSS ratio as high as 1.0 was used and the optimum BOD/N ratio was found to be 3.4. Figure 10 has been prepared from the data in Table 6 to show the relationship between the BOD/MLVSS



NITRATE REDUCTION RATES IN REACTOR TESTS

FIGURE 10

ratio (F) and the rate of nitrate reduction (R). Lines of regression have been computed for the data as follows:

Substrate used	Equation	Correlation coefficient
Milk solids	$R = 7.98F + 0.13$	0.994
Methanol	$R = 7.35F + 0.91$	0.043

The circled data points were not considered in the computations since it was known that in these tests excessive amounts of substrate were used and conditions were not representative of equilibrium considerations. For both substrates the data clearly show a linear relationship between the organic loading rate and the rate of nitrate reduction. This relationship shows that there is a constant ratio between the carbon source used for denitrification and the nitrogen lost by denitrification. The mean BOD/N ratio from Table 6 for the milk solids data is 3.85 and for the methanol data is 3.86. It is only coincidental that these ratios are almost identical. These ratios should not be taken as absolute equilibrium ratios but only as the approximate BOD/N requirements. The work by Barth and his co-workers(7) reported a ratio of 3.3 for a methanol system and under the most ideal conditions the optimum ratio may be found to be less than this value. When using milk solids it was found that operation at close to the optimum ratio of 3.4 produced an effluent nitrate-N concentration of 0.6 mg/l whereas in a parallel test using a ratio of 4.0 the nitrate-N effluent concentration was depressed 0.2 mg/l. These results indicate that the higher ratios may produce effluents with slightly lower nitrate concentrations.

Although the effluent SS concentrations were generally quite high it is believed that this was a hydraulic problem which could be solved in a larger scale operation. The process was shown to be capable of producing low effluent BOD concentrations and the effluent ammonia nitrogen concentrations were shown to be a direct consequence of the nitrogen in the carbon source added directly to the denitrification reactor. The process did not seem to be greatly affected by temperature since denitrification was achieved in 2.6 hours at 10°C.

c. Four Stage Operation

It was shown that a four stage operation was feasible. The first two stages reduced the nitrogen by 67 per cent while the overall removal through the four stages was 86 per cent. Phosphorus removal through the units was quite small.

22. Analyses of Process Over 24-Hour Period

a. Sampling

During Test 20 on February 19 and March 18 effluent samples were taken every two hours. Likewise for Test 22Ab on March 18, effluent samples were again taken every two hours. The results of these tests are presented in Tables 8, 9 and 10 and in Figures 7, 8 and 9. The rate of flow cycle is shown graphically in the figures. The concentrations of solids in the synthetic waste water was constant throughout the flow cycle.

b. Discussion

(1) Nitrification

All samples taken during Test 20 were from a nitrification process, and because there is a limited amount of data no conclusive observations may be made. However the data do indicate some possible trends.

The variation in pH shown in Figure 7 shows two definite periods of differences. Very likely at the low flow condition (and low load condition) there is both less CO_2 production and higher ratios of air flow/waste flow to cause a greater removal of CO_2 and cause a rise in pH.

Suspended solids concentrations on both days seemed to correspond directly with the flow rates as might be expected. There appeared to be more of a

TABLE 8

Test 20 - NITRIFICATION - Feb. 19, 1968

HOURLY VARIABLE FLOW DATA

Time	Flow Rate ml/min	pH	Effluent Concentrations, mg/l SS	TP	COD	TKN	NH_3-N	NO_2-N	NO_3-N
8:00	18.1	7.60	53	2.9	94	5.6	1.9		22.3
10:00	19.3	7.65	68	2.5	79	3.9	0.7		20.8
12:00	18.6	7.65	68	2.2	65	7.8	0.6		19.5
2:00	16.0	7.62	76	2.5	65	2.8	0.6		20.2
4:00	13.0	7.72	24	1.8	60	--	0.8		17.3
6:00	8.6	7.67	28	1.9	45	4.8	0.7		18.3
8:00	6.2	7.62	41	2.2	79	4.2	0.8		19.0
10:00	6.2	7.91	11	2.0	25	3.1	0.5		19.3
12:00	5.3	7.87	13	2.7	0	2.8	0.6		22.0
2:00	5.6	7.88	23	2.4	25	4.5	0.6		20.5
4:00	7.5	7.93	29	2.6	55	8.1	0.7		22.0
6:00	11.8	7.62	17	2.4	25	3.2	0.7		21.5
8:00	16.0	7.65	28	2.3	35	3.8	0.8		20.5

TABLE 9

Test 20 - NITRIFICATION - Mar. 18, 1968

HOURLY VARIABLE FLOW DATA

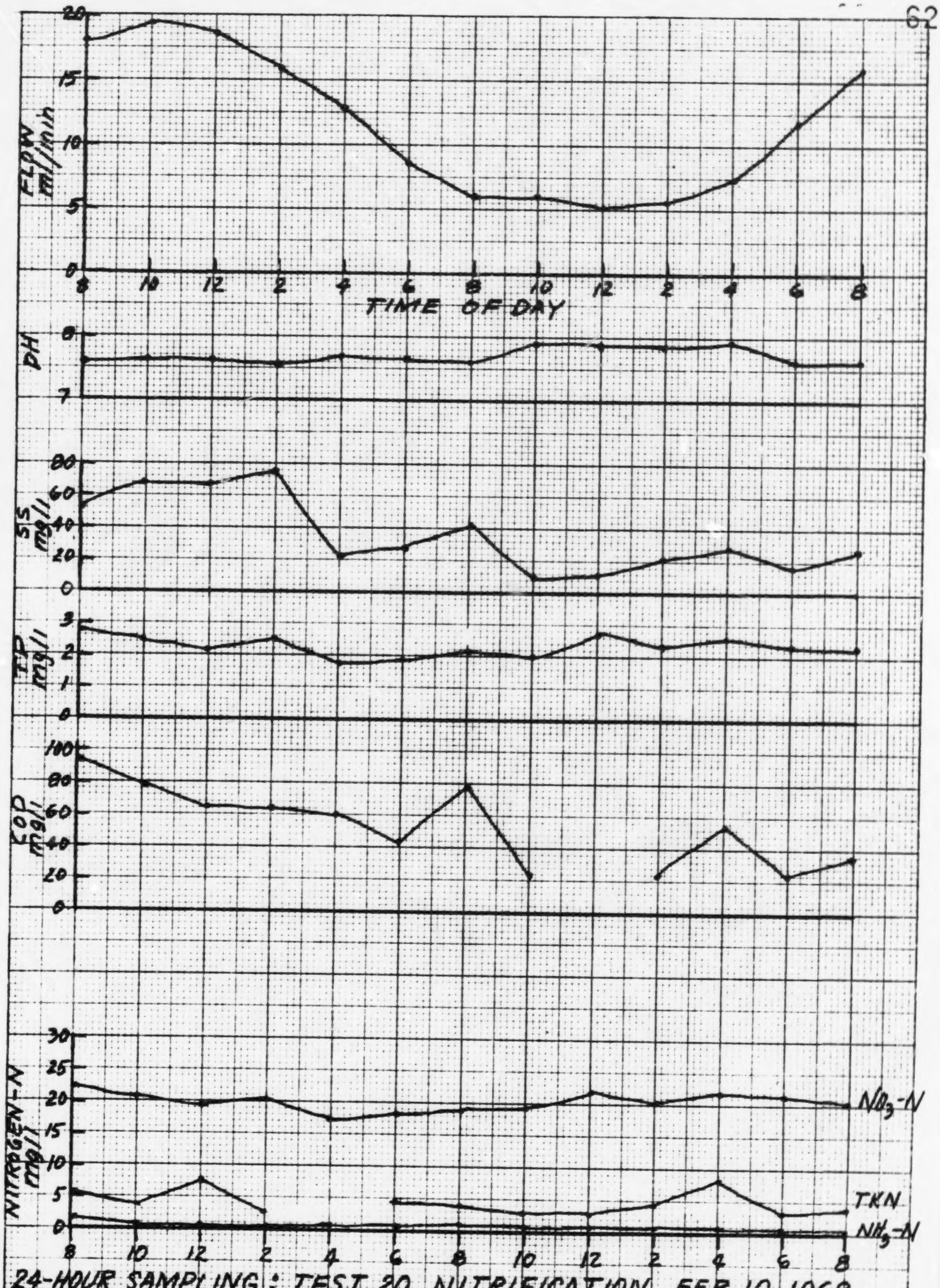
Time	Flow Rate ml/min	pH	Effluent Concentrations, mg/l						
			SS	TP	COD	TKN	NH_3-N	NO_2-N	NO_3-N
6:00	18.3	7.6	22	2.5	30	3.8	0.8	0.04	24.8
8:00	23.5	7.5	18	2.0	39	2.9	0.7	0.07	24.3
10:00	22.0	7.6	23	1.5	39	2.8	0.6	0.06	23.0
12:00	21.0	7.6	21	1.1	32	3.5	0.5	0.05	21.3
2:00	19.2	7.6	18	1.0	32	2.2	0.5	0.05	21.3
4:00	15.5		24	0.9	32	2.2	0.8	0.04	21.7
6:00	10.9		12	1.1	20	1.8	0.4	0.04	17.7
8:00	7.4		13	1.2	20	2.0	0.6	0.04	21.5
10:00	7.9		12	1.4	17	1.5	0.4	0.05	22.0
12:00	6.4		12	1.7	17	1.8	0.4	0.04	21.8
2:00	9.2		12	1.9	24	1.6	0.4	0.05	24.8
4:00	14.4		22	2.8	30	1.7	0.9	0.04	25.5

TABLE 10

Test 22 Ab - DENITRIFICATION - Mar. 18, 1968

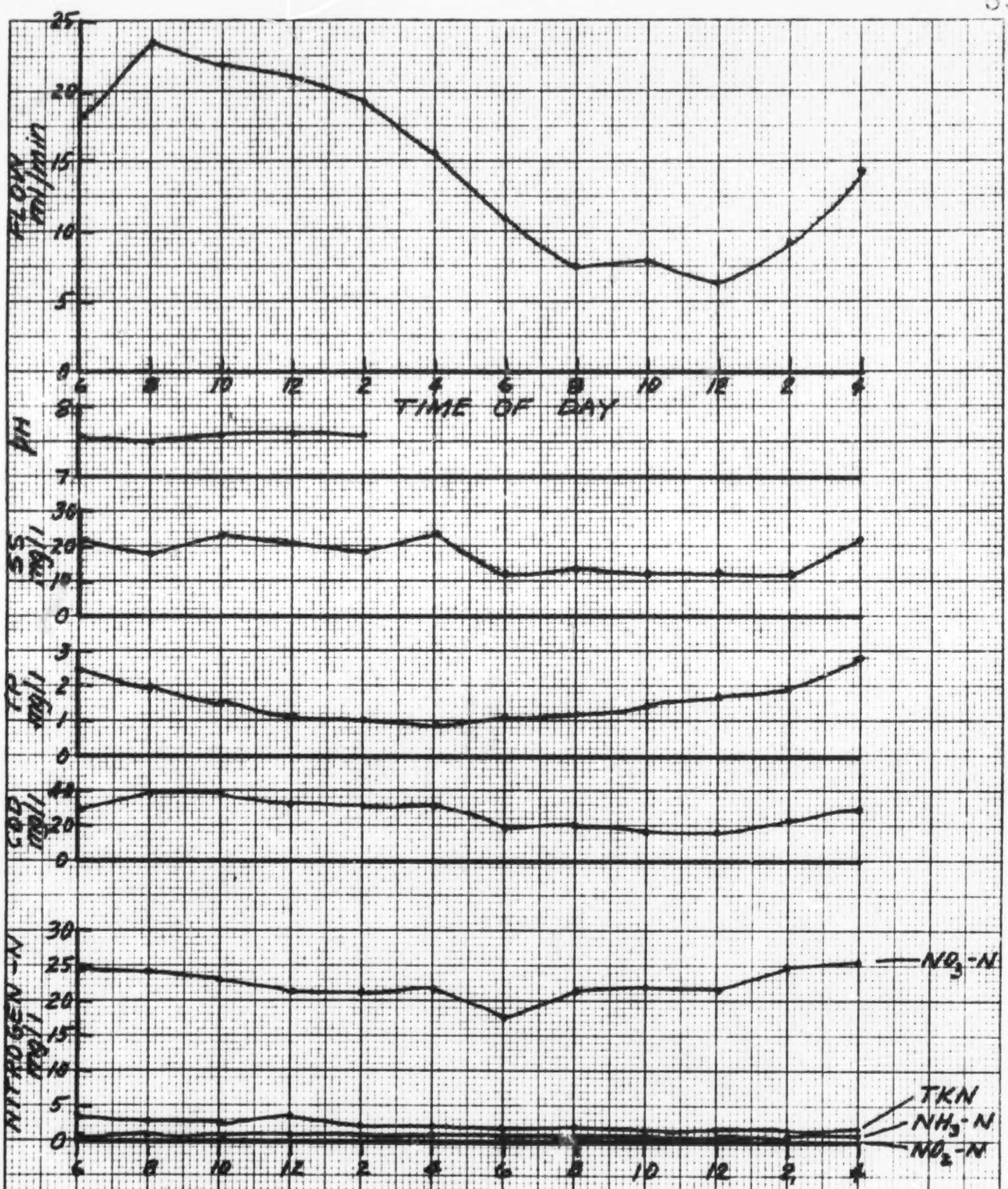
HOURLY VARIABLE FLOW DATA

Time	Flow Rate ml/min	pH	Effluent Concentrations, mg/l						
			SS	TP	COD	TKN	NH_3-N	NO_2-N	NO_3-N
4:00	14.0	7.7	--	0.8	20	6.3	4.6	0.03	0.1
6:00	17.3	7.5	14	0.8	--	2.6	3.9	T	0.1
8:00	20.6	7.4	10	1.0	17	4.2	3.9	0.04	0.1
10:00	22.8	7.6	12	0.7	22	3.9	3.7	0.04	0.1
12:00	23.0	7.5	8	0.6	20	4.1	3.2	0.04	0.1
2:00	22.0	7.4	13	0.6	20	4.1	3.3	0.03	0.1
4:00	19.4	7.5	14	0.7	27	3.7	3.2	0.03	0.1
6:00	15.7	7.9	15	0.8	34	4.2	3.6	0.03	0.1
8:00	12.3	7.6	18	0.9	32	4.4	3.4	0.04	0.1
10:00	8.4	7.6	20	1.0	32	4.8	4.0	0.06	0.1
12:00	9.1	7.7	14	1.1	34	5.3	4.6	0.06	0.1
2:00	8.9	7.6	16	1.1	37	4.9	4.7	0.05	0.1



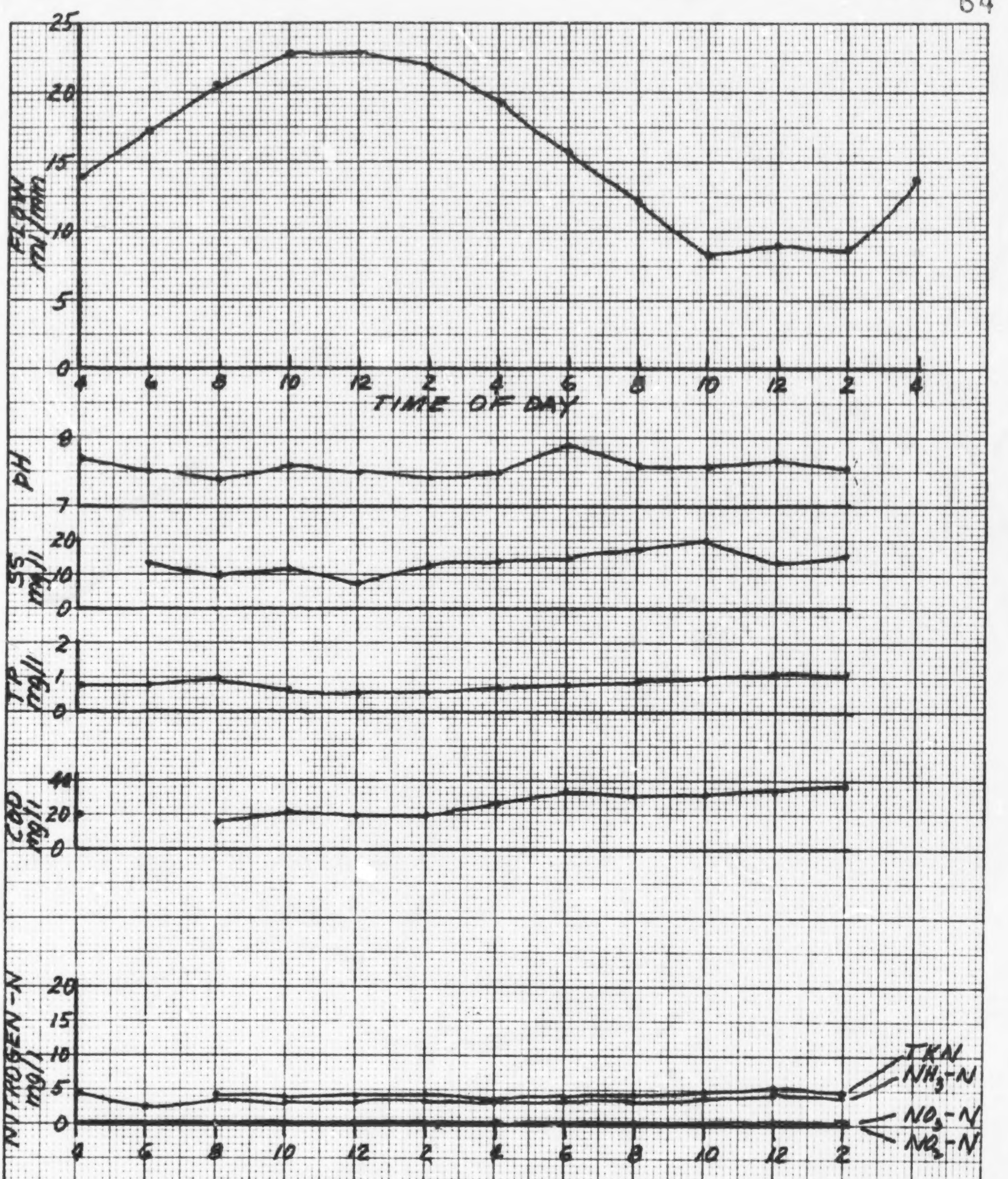
24-HOUR SAMPLING: TEST 20 NITRIFICATION FEB. 19, 1968

FIGURE 7



24-HOUR SAMPLING: TEST 20 NITRIFICATION. MAR. 18, 1968

FIGURE 8



24-HOUR SAMPLING: TEST 22Ab DENITRIFICATION. MAR 18, 1968
FIGURE 9

cyclic variation in total phosphorus on March 18 than on February 17 but nevertheless somewhat the same pattern existed on both days. With higher growth rates during high-flow periods the uptake of phosphorus by the sludge was likely to be greater and thereby diminish effluent concentrations as shown. Although these values were for total phosphorus the values for soluble phosphorus showed a similar pattern.

The COD showed somewhat similar variations on both days with one period of minimum concentration and one of maximum concentration. The data shown are for total COD including SS but soluble COD concentrations were also determined and showed a similar variation. There appears to be a direct correlation of COD with flow rate.

Nitrogen variations are also shown and the TKN values are for total nitrogen including that in the SS. The TKN values showed a slight correlation with the SS concentrations as might be expected, and the remaining soluble fractions were so low that they were of little concern. Ammonia concentrations were for the most part less than 1.0 mg/l and showed no apparent change with the flow rate. The fact that the ammonia concentrations were reasonably constant is significant when observing the nitrate variations. The nitrate concentrations showed a cyclic pattern similar to the flow rate. The minimum nitrate concentration occurred approximately 6 hours following the maximum flow, and the maximum nitrate concentration occurred 4-6 hours following the minimum flow rate. However, the total effluent nitrate variation may not be significant since it was only 17-22 mg/l and 18/25 mg/l. Despite the variation in nitrates there was not a corresponding variation in ammonia and from this it is indicated that the variation of sludge growth rate with load results in greater net nitrogen uptakes during these periods. The consequence of this is that less ammonia remains to be oxidized and consequently the actual nitrate concentrations become less for a period following a high flow (or load).

(2) Denitrification

The data obtained during Test 22Ab was from a denitrification test. It is noted from Table 6 that the BOD/N ratio was reasonably low and consequently the effluent BOD or COD should be quite low.

The changes in pH over the 24-hour period are hardly worth noting although the slightly higher values during the low flow period may be due to the lower rate of production of CO_2 and higher ratios of mixing gas/waste flow. The SS, TP and COD changes were essentially directly correlated with one another. Since the TP and COD values included the SS one would expect this sort of pattern. Changes in the soluble fraction were, however, not evident. Although effluent SS should normally vary directly with the flow rate, the maximum concentrations were found with lower flows. The total variation in SS concentration, however, was only from 8 to 20 mg/l. With a reasonable allowance for the COD of the effluent SS it is evident that the soluble COD in the effluent would be in the range of only 10-30 mg/l.

The milk solids and sodium nitrate used as the influent to the process contributed the following concentrations of nitrogen and phosphorus.

	P, mg/l	N. mg/l
Milk solids:		
TP -	1.8	
TKN -		7.0
Sodium Nitrate:		21.2
Total	1.8	28.2

With some allowance for the uptake of N and P in the sludge it is evident that the remaining quantities of N and P from the milk solids are found in the effluent. Essentially all of the nitrate nitrogen was lost due to denitrification and the overall removal was approximately 85 per cent.

The ammonia-N concentrations shown in Table 10 indicate a greater uptake of nitrogen during the period of high flow (high organic load). The variation is small but consistent and is likely due to higher net growth during the high load periods. The fact that the effluent nitrogen concentration variations are small is a favourable output characteristic, and the low nitrate concentration is attributed to the use of a BOD/N ratio of the proper order of magnitude and maintaining the same ratio throughout the flow cycle.

VI. DEMONSTRATION PLANT TESTS

A. Test Program

With the background gained from the reactor tests using synthetic feed solutions, it was decided to test the process using a municipal wastewater. The significance of using a municipal waste is not only that the composition differs from that of the synthetic waste, but there also is an inherent time variation in concentration associated with it. However, to completely simulate flow in a small demonstration plant with that of a municipal plant, it is necessary to provide some means of continuously varying the rate of flow.

A demonstration plant was constructed and located at Minneapolis-St.Paul Sanitary District (MSSD) Wastewater Treatment Plant, and primary effluent was used as the wastewater feed. The device developed for the variable flow reactor tests was used to provide a continuously varying rate of flow to the demonstration plant.

The objectives of the test program were to determine whether or not a municipal wastewater could be treated for nitrogen removal using processes and procedures similar to those defined in the reactor tests. As such, the basic flow diagrams shown in Figure 3 were used where the conventional activated sludge process was used for nitrification. Denitrification was achieved with a mixed anaerobic reaction tank followed by a settling tank with sludge recycle to the mixed tank. Primary effluent was used as the carbon source and was fed to the denitrification unit together with the nitrified effluent from the nitrification unit.

Tests were conducted at both constant and variable rates of flow. Temperature variations were encountered as the seasonal variations in the raw wastewater temperature were experienced.

B. Equipment

1. General

The demonstration plant was located in the aeration gallery of the MSSD Treatment Plant. It was fortunate to obtain this location because of the protection of the plant from the weather and the availability of electrical power, compressed air, sampling facilities, and the primary effluent feed for the demonstration plant. The plant was designed for a nominal average flow of (1) one gallon per minute.

Immediately adjacent to the gallery was a channel with primary effluent, and fortunately there were valved pipes through the wall to supply the demonstration plant with a raw feed.

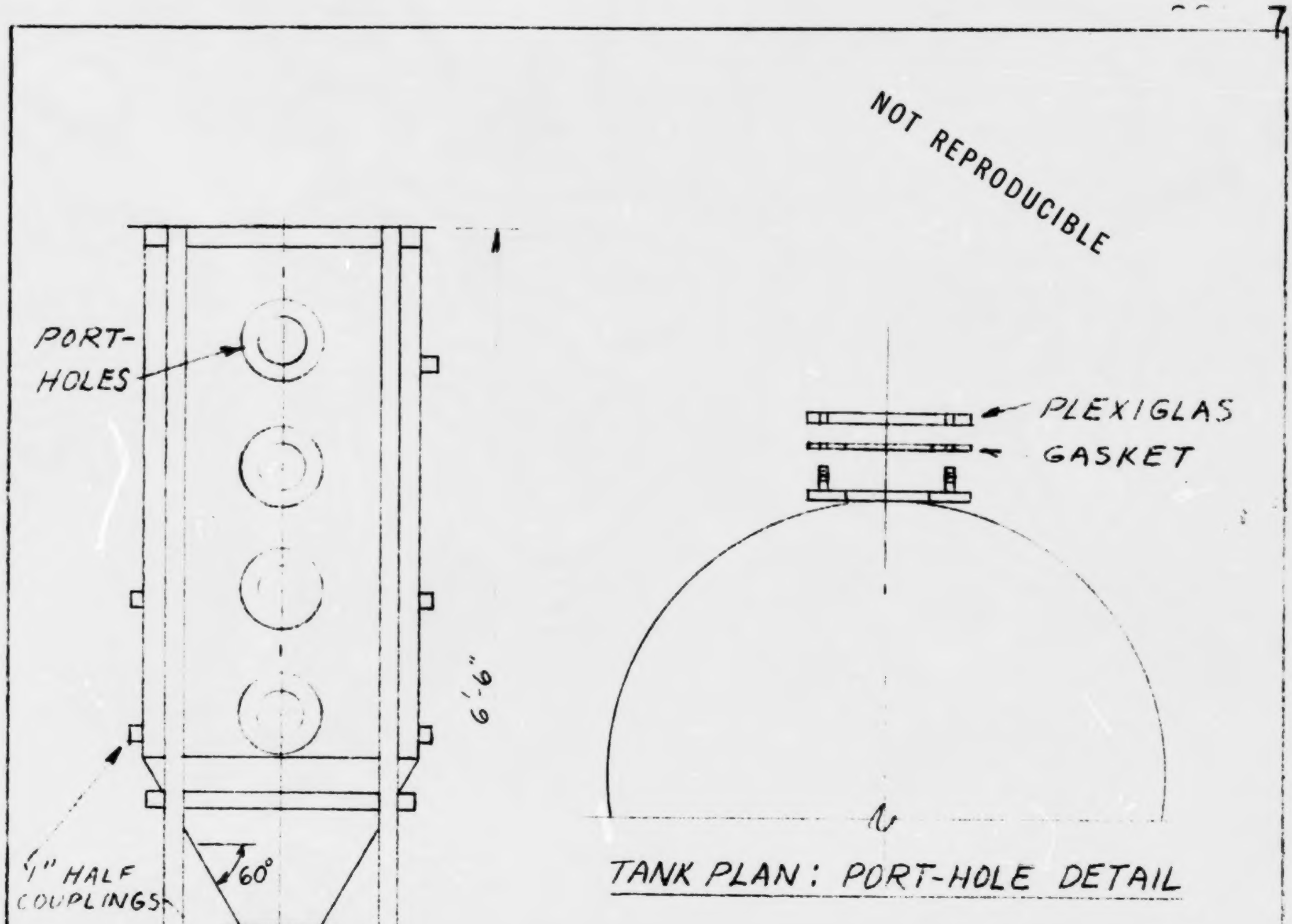
2. Reaction Tanks

The reaction tanks consisted of seven (7) 2'-0" diameter tanks and two (2) 3'-0" diameter tanks. Each tank was 6'-6" high and constructed of 16 gauge galvanized steel. A typical tank is shown in Figure 11. The 2'-0" diameter units had hopper bottoms with 60° slopes while the 3'-0" diameter units had bottom cones with 45° slopes.

Each tank could be used either as an aeration tank or settling tank. When used as an aeration tank air was added to the tank at the bottom of the cone and diffused through a layer of wire and saran fabric placed between the two flanges located approximately 6 inches above the cone bottom. The fabric and wire were removed when the tank was to be used as a settling tank and the sludge was removed at the cone bottom.

Portholes were constructed as shown in four of the 2'-0" diameter tanks in order to observe the sludge mixing and sludge levels in the tanks. The port-holes were covered with plexiglas and served their purpose well. It would have been advantageous to have port-holes on all of the tanks.

NOT REPRODUCIBLE


TANK-ELEVATION

TANK PLAN: PORT-HOLE DETAIL

TANK - PLAN

BOTTOM FLANGE DETAIL

PORT-HOLES
6'-6"
1" HALF COUPLINGS
60°
PLEXIGLAS
GASKET
1½" PIPE LEGS
2'-0" or 3'-0"
16 GA. GALV. TANK
6" or 9"
FOR AIR DIFFUSION INSERT WIRE MESH AND CLOTH

DEMONSTRATION PLANT TANKS - CONSTRUCTION DETAILS

FIGURE 11

It was originally intended to interconnect the tanks with 1" diameter vinyl tubing. It was later found that air binding was occuring in these lines and by switching to 1½" diameter tubing most of these operational problems were avoided.

For denitrification the reaction tank required mixing without aeration. Initially the reaction and settling tanks were covered and sealed in order to recirculate gases for mixing as done in the reactor tests. For a number of reasons this method of mixing was impracticable and straight mixing with a propellor-type unit was used. Despite the air-liquid interface and the need for anaerobiosis, there was no apparent evidence that excessive amounts of ocygen were being transferred across the interface.

The tank assemblies and individual tanks are shown in photographs as Figures 12, 13, and 14.

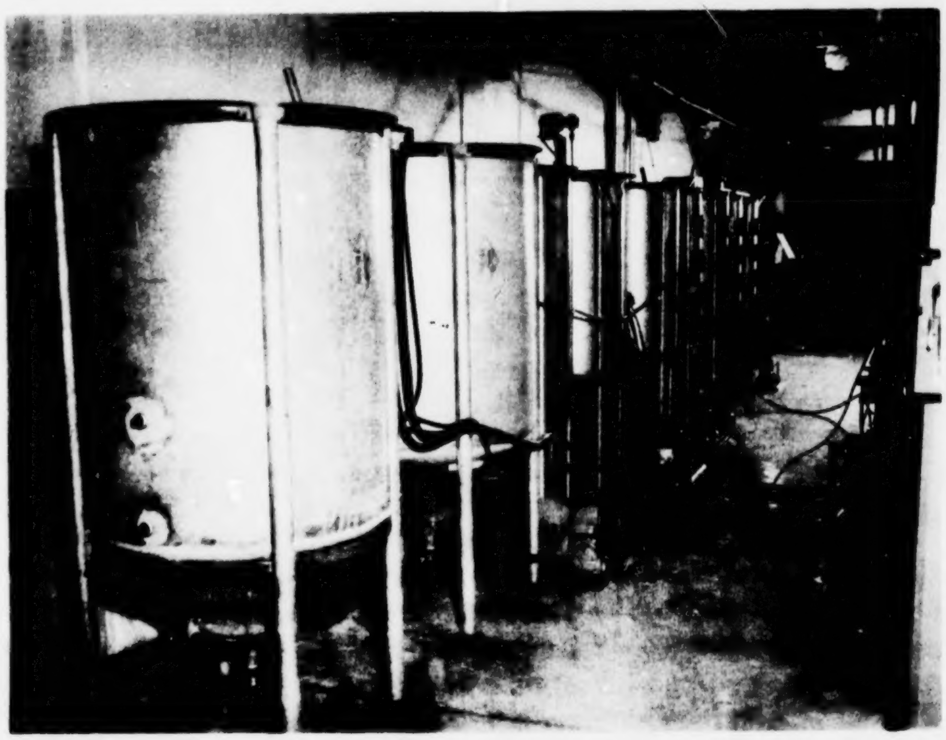
3. Air Supply

The air was supplied from the MSSD plant and furnished to the individual tanks through a series of valves as shown in the photograph, Figure 15. As shown in the photograph, four air lines were available for the tanks and each supply was metered through the one rota-meter.

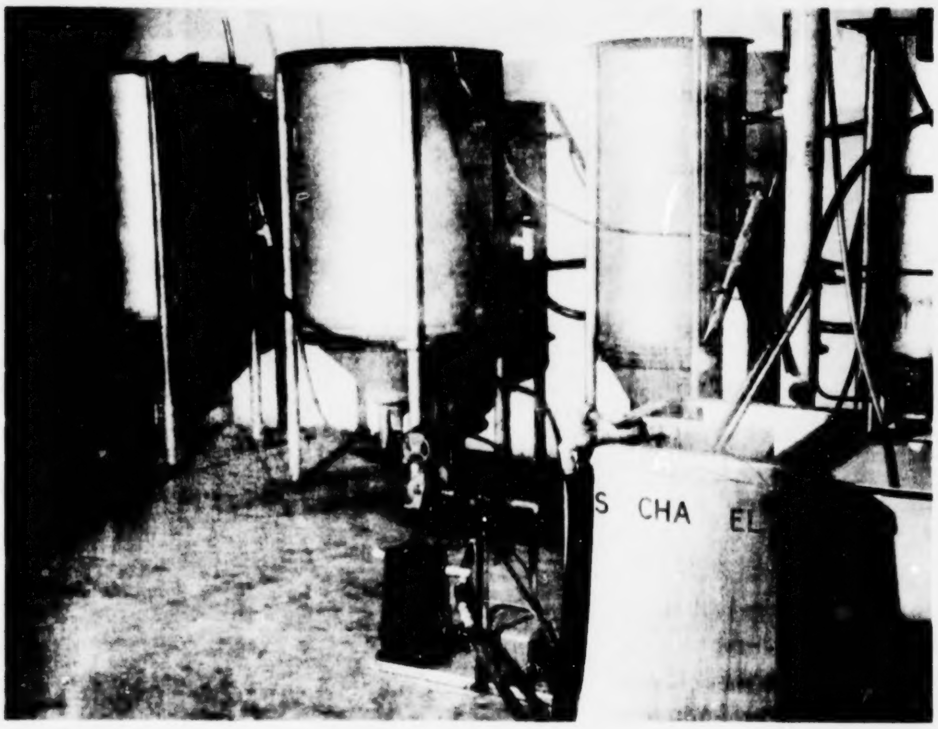
4. Pumps and Feed Apparatus

All pumps were Sigmamotor pumps with the exception of one Moyno pump. The Moyno pump was equipped with a U.S. Motor Vari-Drive but operated at a constant rate of flow on the return sludge line for the initial nitrification process.

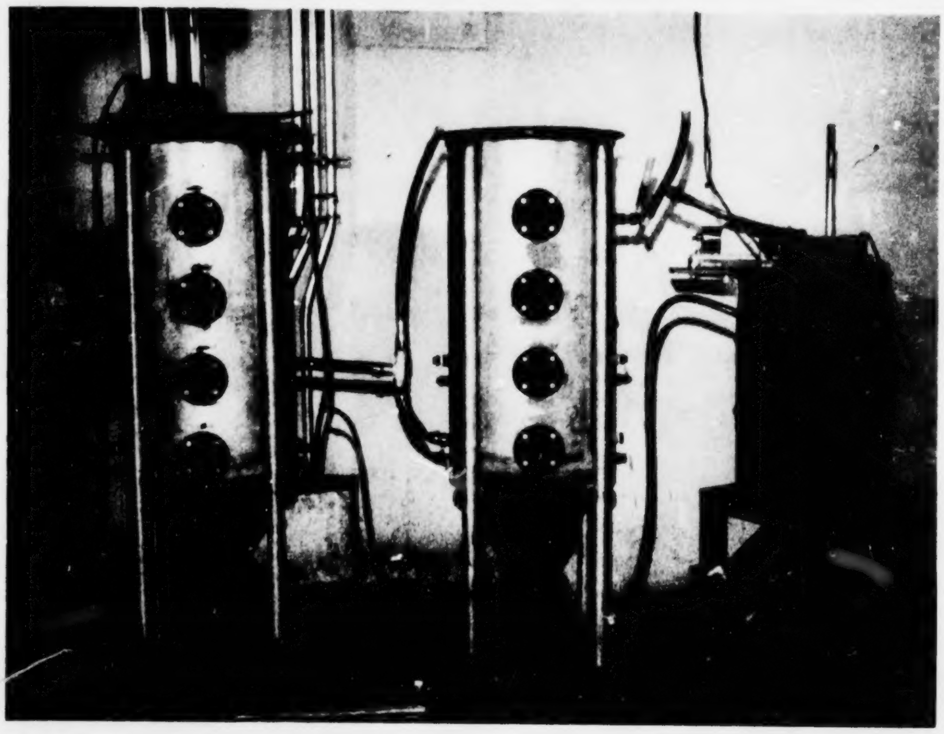
The Sigmamotor pumps were equipped with Zero-Max speed reducers. All of the Sigmamotor pumps were Model T-6 units except for the raw feed pump to the first nitrification unit which was a Model T-4. The T-4 unit was also equipped with an actuating lever to provide a continuously



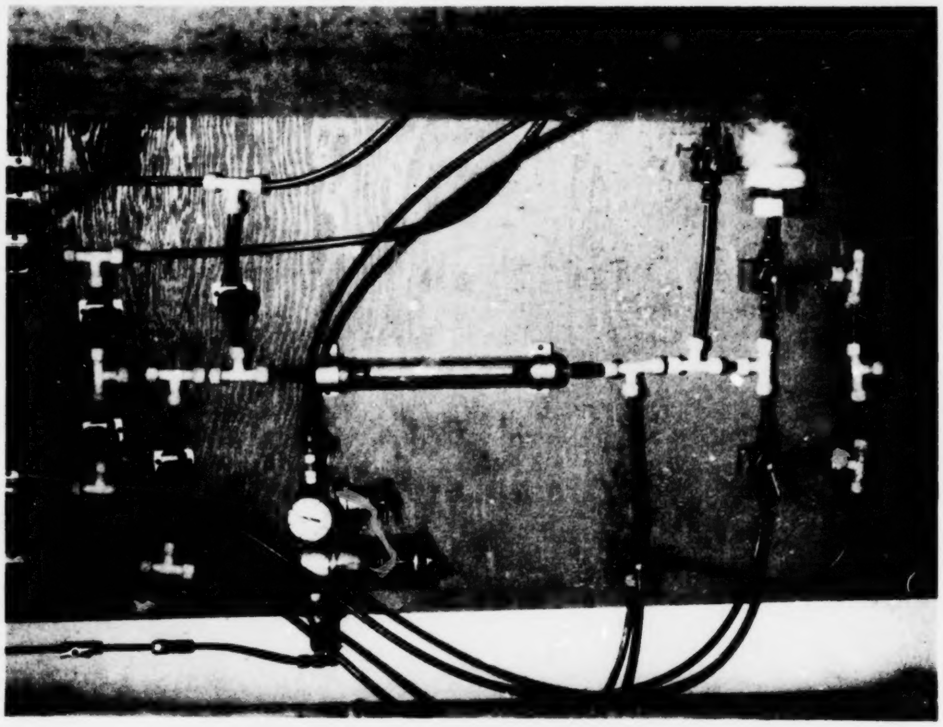
DEMONSTRATION PLANT ASSEMBLY. FIGURE 12



DEM. PLANT: AER. TANKS, PRIMARY PUMP & SAMPLER. FIGURE 13



DEM. PLANT: DENITRIFICATION TANKS & SIPHON BARREL. FIGURE 14



DEM. PLANT: AIR METERING BOARD. FIGURE 15 varying rate of flow. Typical pump installations are shown on Figures 12, 13 and 14, and the T-4 Sigmamotor pump with the variable flow equipment is shown as Figure 16.

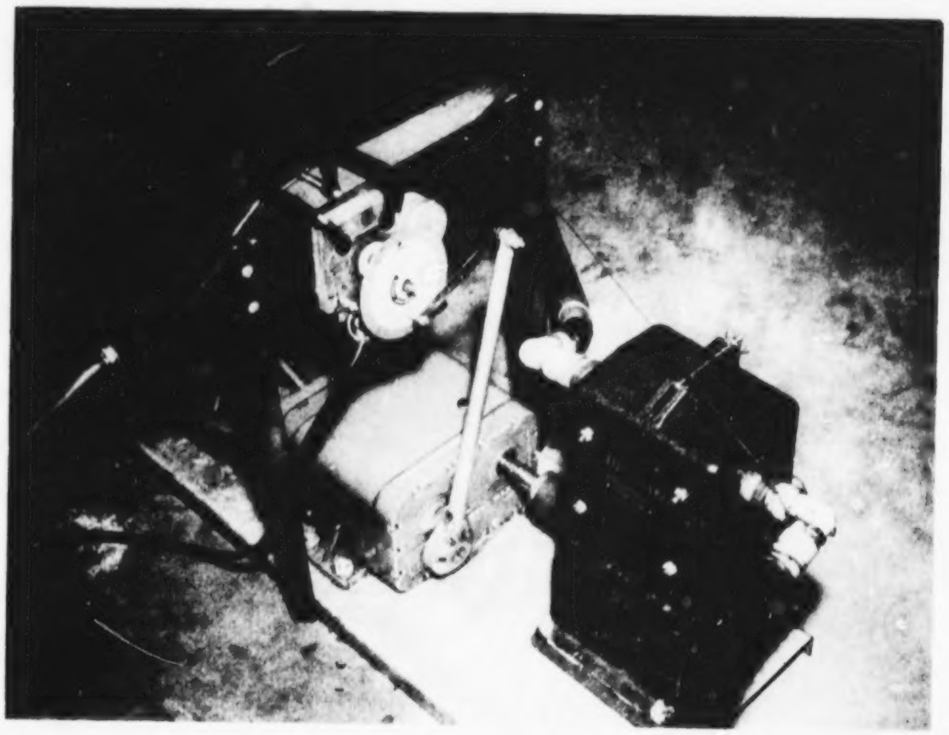
Because there was a delay in obtaining the large feed pump the initial method of supplying primary effluent was through the use of an orifice. The orifice was at the bottom of a plexiglas tube with an inner tube used as an overflow. The inner tube was adjustable in height to provide a means of adjusting the rate of flow. This system was only temporarily used and was undesirable because of the tendency to clog.

5. Deaeration Tank

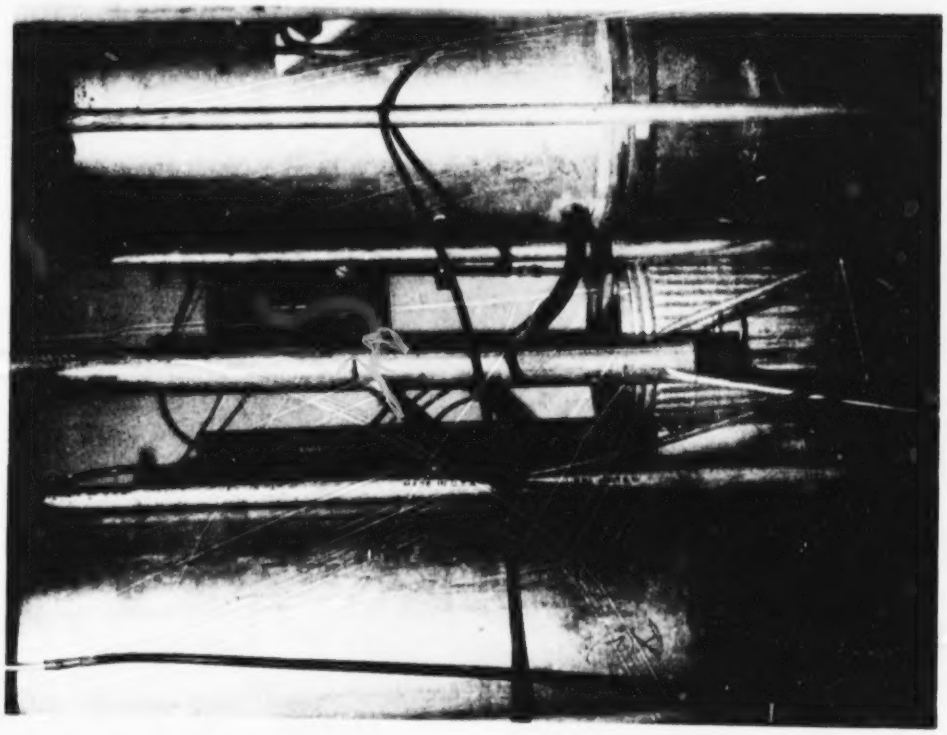
With the release of nitrogen gas as one of the end products of denitrification, some problems were encountered with gas-lifting in the final settling tank. To alleviate this condition a degasification tank was constructed based on some aeration tests followed by settling. It was concluded that a 4" diameter tank giving a nominal aeration period of two minutes would be very adequate and hopefully would not add a great deal of dissolved oxygen. The tank as constructed was as shown in the photograph, Figure 17, in the center of the picture. Air was introduced at the bottom and the flow was from left to right.

6. Flow Metering

Instantaneous rates of flow were measured volumetrically using a large flask. The raw waste feed lines and return sludge lines were all equipped to permit measurment in this way at any time. A record of total plant flow was obtained by using a siphon barrel at the outlet end of the system. The final effluent drained into a 55 gallon drum equipped with a siphon which would discharge when filled to approximately the 45 gallon level. By using a level recorder in the tank, each filling of the barrel



DEM. PLANT: PRIMARY FEED PUMP. FIGURE 16



DEM. PLANT: DEAERATION TANK. FIGURE 17

was noted by a high point on the recorder chart. The number and spacing of the points on the recorder chart was used as a record of the rate of flow through the plant. The equipment is shown in the photograph, Figure 14.

This effluent barrel also served as a means of providing a signal for the samplers to operate. Whenever the barrel was full a float switch operated to actuate the composite samplers.

7. Sludge Wasting

Sludge wasting from the nitrification process was accomplished by wasting mixed liquor as suggested by Garrett(35). A flexible hose was connected to the aeration tank and a rubber section of the hose was flattened against a base board by a spring loaded bar. The bar was connected to two solenoid switches which periodically lifted the bar to open the hose and thereby waste mixed liquor. A five-minute timer was used such that sludge was wasted every five minutes and for any fraction thereof. By adjusting the time interval it was possible to maintain a reasonably constant mixed liquor solids concentration.

8. Sampling

Sampling was usually accomplished through the use of automatic samplers. All samplers used were as manufactured by Sonford Products Corporation of Minneapolis.

The effluents from the nitrification and denitrification plants were sampled using the Model HG-2 samplers and the primary effluent was sampled with a Model TC-2 which was already in place as part of the MSSD equipment. The samples taken with these samplers were composite samples and operated on a signal from a float switch in the effluent barrel.

On several occasions samples were taken hourly by use of Model NW-2 samplers from the Sonford Products Corporation.

C. Procedures

The demonstration plant was operated by personnel from the University of Minnesota except for some equipment maintenance work and general observations. Employees of the MSSD on duty in the location of the demonstration plant were very helpful in notifying the investigators of unusual operating conditions. The analytical laboratory at the MSSD did provide help in running some BOD's, but for the most part the analytical work was conducted in the Sanitary Engineering Laboratories at the University of Minnesota.

The demonstration plant was visited at least once each day and sometimes as often as three times during a 24-hour period. These visits were for performing routine preventive maintenance, taking samples, adjusting operating conditions, and solving many unpredicted problems. Mechanical problems included: clogged tubing due to solids or air binding; broken tubes; pump and motor failure; samplers inoperative; frozen feed lines; and power failure. Operational problems included: rising sludge in settling tanks; bulking sludge; and necessary shut-downs due to curtailing of MSSD operations. In explanation of the latter, it was necessary to curtail the MSSD operations due to mechanical equipment failure and due to high water conditions in the receiving river. At one period the entire plant was shut down because of the danger of flooding.

The consequences of these mechanical and operational problems are somewhat obvious. Flow interruption of any sort cause upsets of equilibrium situations, and the occasional loss of activated sludge solids resulted in having to repeat certain test operations.

Because of the many interruptions of the operations the data have been analyzed for the periods shown in Table 11 during which times it was considered that valid data were obtained. It is also noted in the table whether or not the primary feed rate was constant or variable. Also shown are the days on which hourly samples were taken.

D. Experimental Results of Demonstration Plant Tests

1. General Test Conditions

Data from the demonstration plant tests were analyzed for test periods shown in Table 11. Because of the operational problems encountered all of the data obtained were not sufficient for analysis. In Table 11 the test number desigration is shown, each test is shown to have been operated with constant or variable flow, and data are shown when hourly samples were taken over 24-hour periods.

The operational data are presented in Table 12 where mean, maximum and minimum values are given. Flow is given in milliliters per minute (ml/min). Observations of concentrations in the mixed liquor in milligrams per litre (mg/l) are given as dissolved oxygen (DO), suspended solids (SS), and volatile suspended solids (VSS). Air used is expressed in cubic feet per minute (cfm), and detention times (DT) are given in hours (hrs). The organic load to the reactors is expressed as ratios of pounds of 5-day 20°C BOD per day per pound of mixed liquor volatile suspended solids under aeration (BOD/MLVSS), and as the weight of BOD per day per pound of mixed liquor suspended solids otherwise known as sludge age (SA). The sludge volume index is given (SVI) together with the percent that the rate of flow of return sludge is of the raw flow. Settling tank characteristics are given in terms of detention time (DT) in hours (hrs) and surface settling rates (SSR) as gallons per day per square foot (gpd/sf).

Table 11. Listing of Demonstration Plant Test Periods

Test No	Dates	Constant(C) or Variable(V) feed	Dates for which hourly data were obtained
1	Nov 1-7, 1968	C	
2	Nov 9-14, 1968	C	
3	Nov 17-21, 1968	C	
4	Nov 22-Dec 1, 1968	V	
5	Dec 6-11, 1968	V	
6	Dec 12-18, 1968	V	
7	Dec 31-Jan 5, 1969	V	
8	Jan 6-9, 1969	V	Jan 6-9, 1969
9	Jan 10-19, 1969	V	
10	Jan 20-29, 1969	V	
11	Feb 24-Mar 8, 1969	C	
12	Mar 19-26, 1969	C	
13	Mar 27-29, 1969	V	
14	Mar 31-Apr 3, 1969	C	
15	Apr 7-9, 1969	C	Apr 6-9, 1969
16	May 12-15, 1969	C	
17	May 19-26, 1969	C	
18	May 27-July 22, 1969	V	June 4-6, 1969 June 16-20, 1969 July 10-11, 1969
19	July 24-Aug 21, 1969	C	

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT				Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	BOD MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
1. Nov. 1 - 7,1968 - C												
N: No. of Obs.	7	16	6	6	7	7	7	7	6	7	7	7
Mean	2629	3.4	4703	3594	2.21	11.5	0.11	14.3	52	53	2.2	318
Min.	2400	0.6	4200	3310		11.0	0.08	11.0	46	52	2.1	290
Max.	2750	6.3	5350	4284		12.6	0.13	13.9	67	62	2.4	332
D: No. of Obs.	6	3	5	5		6	5	5		6	6	6
Mean	708	0.8	1304	913		1.7	0.56	2.8		12	1.7	408
Min.	600	0.5	600	292		1.6	0.30	1.9		10	1.6	387
Max.	950	1.2	2100	1478		1.8	1.46	4.8		15	1.8	442
T: No. of Obs.	6											
Mean	3337											
Min.	3200											
Max	3650											
2. Nov. 9-14, 1968 - C												
N: No. of Obs.	6	20	4	4	5	6	4	4	4	6	6	6
Mean	2625	3.0	4877	3476	2.14	11.6	0.13	13.4	69	58	2.2	317
Min.	2500	0.7	4120	2988		10.8	0.11	8.2	63	50	2.1	302
Max.	2800	4.9	5470	3906		12.1	0.17	13.5	77	71	2.3	339
D: No. of Obs.	6	4	3	3		6	3	3		4	6	6
Mean	890	0.2	1980	1387		1.7	0.60	2.6		19.5	1.7	425
Min.	740	0.1	1450	1022		1.6	0.40	1.9		13.0	1.6	406
Max.	980	0.3	2620	1840		1.7	0.80	3.6		28.4	1.7	448
T: No. of Obs.	6											
Mean	3515											
Min.	3360											
Max.	3610											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT	BOD			Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
3. Nov.17-21,1968 - C												
N: No. of Obs.	4	20	3	3	5	4	3	3	3	3	4	4
Mean	2700	1.8	5442	3968	2.18	11.3	0.11	12.2	91	66	2.1	327
Min.	2400	0.6	5360	3940		10.1	0.10	11.0	82	61	1.9	290
Max.	3000	2.6	5450	4024		12.6	0.13	14.5	103	74	2.4	363
D: No. of Obs.	4	3	3	3		4	3	3				
Mean	762	0.4	1169	836		1.7	0.72	2.1				
Min.	720	0.2	536	368		1.5	0.42	1.1				
Max.	800	0.6	1882	1350		1.8	1.23	3.3				
T: No. of Obs.	4											
Mean	3462											
Min.	3150											
Max	3800											
4. Nov. 22- Dec. 1, 1968 - V												
N: No. of Obs.	4	12	4	3	4	4	1	2	4	1	4	4
Mean	2575	2.3	4421	3251	2.39	11.9	0.10	10.8	104	76	2.3	312
Min.	2100	0.4	4074	3000		10.1		9.2	86		2.1	254
Max.	2800	4.0	4598	3390		14.4		13.1	118		2.8	339
D: No. of Obs.	5	2	2	2		3	2	2				
Mean	680	0.7	910	643		1.9	1.1	1.7				
Min.	650	0.5	514	364		1.7	0.6	0.9				
Max.	720	1.0	1306	922		2.1	1.5	2.4				
T: No. of Obs.	3											
Mean	3255											
Min.	2750											
Max.	3420											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT				Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	BOD/MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
5. Dec. 6-11, 1968 - V												
N: No. of Obs.	2	9	3	3	3	2	2	2	3	2	2	2
Mean	2663	3.8	4437	3187	2.23	11.4	0.16	8.7	111	65	2.2	322
Min.	2600	3.4	4138	2874		11.1	0.15	8.5	89	60	2.1	314
Max.	2725	4.7	4706	3456		11.6	0.17	9.2	133	70	2.2	329
D: No. of Obs.	3	3	3	3		2	2	2		2	2	2
Mean	740	0.2	1694	1188		1.8	0.47	3.2		29	1.8	401
Min.	700	0.1	1040	690		1.8	0.37	2.8		24	1.8	399
Max.	800	0.3	2050	1474		1.8	0.52	3.8		33	1.8	402
T: No. of Obs.	2											
Mean	3300											
Min.	3275											
Max	3325											
6. Dec. 12-18, 1968 - V												
N: No. of Obs.	1	9	3	2	2	1	1	1	3	1	1	1
Mean	2500	2.5	4426	3425	2.18	12.1	0.12	11.5	137	56	2.3	302
Min.		0.9	4138	3328					112			
Max.		4.3	4704	3522					164			
D: No. of Obs.	3	1	2	2		1	1	1		1	1	1
Mean	706	0.2	1909	1397		1.8	0.45	3.5		22	1.8	387
Min.	700		1908	1216								
Max.	720		1910	1576								
T: No. of Obs.	1											
Mean	3206											
Min.												
Max.												

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/1			Air	DT				Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	BOD/MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
7.Dec.31,1968-Jan.5,1969 -- V												
N: No. of Obs.	2	4	2	1	2	2	1	2	2	1	2	2
Mean	3035	4.9	3704	3122	2.35	10.0	0.12	9.0	130	52	1.9	367
Min.	2970	4.2	3244			9.8		6.9	114		1.9	359
Max.	3100	4.3	4164			10.2		11.4	149		1.9	375
D: No. of Obs.	2	2	2	1		2	1	2		1	2	2
Mean	675	0.3	2747	2396		1.6	0.16	6.2		43	1.6	449
Min.	650	0.3	2254			1.5		4.5			1.5	438
Max.	700	0.3	3240			1.6		8.4			1.6	460
T: No. of Obs.	2											
Mean	3710											
Min.	3620											
Max	3800											
8. Jan. 6 - 9, 1969 -- V												
N: No. of Obs.	4	8	2			4		2	2	1	4	4
Mean	2955	4.4	4214			10.2		8.1	136	51	2.0	358
Min.	2900	2.0	3964			10.1		7.9	121		1.9	351
Max.	3000	5.9	4464			10.4		8.3	151		2.0	359
D: No. of Obs.	3	2	2			3		1		1	3	3
Mean	657	0.1	3346			1.8		4.7		42	1.8	399
Min.	630	0.1	2816			1.6					1.6	312
Max.	690	0.1	3876			2.3					2.3	446
T: No. of Obs.	3											
Mean	3612											
Min.	2580											
Max.	3690											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor										Sed Tank	
	Flow	Mixed Liquor mg/l			Air	DT	BOD			Ret Sl	DT	SSR
	ml/min	DO	SS	VSS	cfm	hrs	MLVSS	SA	SVI	%	hrs	gpd/sf
9. Jan.10-19,1969 -- V												
N: No. of Obs.	10		1	1		3	1	1	2	2	3	3
Mean	2870		4396	3266		10.5	0.12	11.0	174	52	2.2	347
Min.	2600					10.5			166	46	2.0	345
Max.	2890					10.6			181	57	2.5	349
D: No. of Obs.	2		3	1		2	1	2		1	2	2
Mean	740		2290	1388		1.6	0.35	4.1		36	1.6	437
Min.	720		1842			1.6		3.8			1.6	437
Max.	760		3184			1.6		4.4			1.6	437
T: No. of Obs.	2											
Mean	3610											
Min.	3610											
Max	3610											
10. Jan. 20-29, 1969 -- V												
N: No. of Obs.	10	2	3	3	1	2	2	2	3	2	2	2
Mean	2813	4.6	3172	2741	2.55	10.9	0.20	6.6	165	61	2.1	336
Min.	2600	3.8	3128	2376		10.2	0.19	6.2	160	57	2.0	314
Max.	2960	5.4	3200	2436		11.6	0.21	7.7	169	65	2.2	358
D: No. of Obs.	6		4	4		4	3	3			4	4
Mean	400		1880	1383		1.8	0.28	5.1			1.8	389
Min.	330		1644	1208		1.8	0.19	4.2			1.8	370
Max.	460		2186	1600		1.9	0.32	6.9			1.9	401
T: No. of Obs.												
Mean	3213											
Min.	3060											
Max.	3320											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor									Ret	Sed Tank	
	Flow	Mixed Liquor mg/1			Air	DT	BOD			Sl		
	ml/min	DO	SS	VSS	cfm	hrs	MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
11.Feb.24-Mar.8,1969 -- C												
N: No. of Obs.	10	36	10	9	10	10	9	10	10	10	10	10
Mean	4100	4.9	2915	2063	3.10	7.4	0.34	4.1	200	54	1.4	498
Min.	4000	3.0	2534	1850		7.2	0.29	3.9	136	43	1.4	484
Max.	4200	6.7	3438	2402		7.6	0.41	5.5	270	70	1.4	518
D: No. of Obs.	9	7	9	8		9	7	8		1	9	9
Mean	376	0.2	1256	938		1.3	0.39	3.7		21	1.3	541
Min.	300	0.1	816	622		1.2	0.19	2.2			1.2	530
Max.	420	0.3	2095	1430		1.3	0.52	7.8			1.3	558
T: No. of Obs.	9											
Mean	4476											
Min.	4385											
Max	4620											
12. Mar. 19-26, 1969 -- C												
N: No. of Obs.	6	12	6	6	6	6	6	6	6	6	6	6
Mean	3467	4.6	3507	2378	2.41	8.7	0.21	7.0	164	104	1.7	419
Min.	3200	3.0	3212	2174		7.9	0.15	5.9	103	100	1.5	387
Max.	3800	5.8	3862	2648		9.4	0.26	8.6	240	109	1.8	460
D: No. of Obs.	6	6	6	6		6	6	6		1	6	6
Mean	563	0.5	2361	1494		1.5	0.28	6.1		28	1.5	470
Min.	365	0.4	1748	1148		1.4	0.15	3.6			1.4	436
Max.	880	0.6	2952	1556		1.6	0.43	11.0			1.6	513
T: No. of Obs.	6											
Mean	3832											
Min.	3600											
Max.	4245											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT	BOD			Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
13. Mar.27-29, 1969 -- V												
N: No. of Obs.	3	8	1	1	6	3	1	1	1	2	3	3
Mean	3104	4.6	3448	2396	2.39	9.8	0.16	8.8	250	112	1.9	375
Min.	3060	2.1				9.6				111	1.8	370
Max.	3150	6.4				9.9				113	1.9	381
D: No. of Obs.	3	1	1	1		1	1	1			3	3
Mean	556	0.6	3324	2256		1.6	0.16	9.3			1.6	443
Min.	500					1.5					1.6	431
Max.	590					1.6					1.6	452
T: No. of Obs.	3											
Mean	3660											
Min.	3560											
Max	3740											
14. Mar.31-Apr. 3, 1969 -- C												
N: No. of Obs.	4	12	4	4	4	4	4	4	4	4	4	4
Mean	3212	3.7	2946	2011	2.39	9.5	0.24	5.9	263	116	1.8	388
Min.	2850	2.4	2910	1982		8.3	0.22	5.4	224	99	1.6	345
Max.	3650	5.0	2982	2022		10.6	0.27	6.5	303	130	2.0	441
D: No. of Obs.	4	3	4	4		4	4	4			4	4
Mean	600	0.4	2448	1672		1.5	0.28	5.5			1.5	461
Min.	490	0.4	1988	1388		1.4	0.22	4.4			1.4	433
Max.	730	0.5	3081	2224		1.6	0.34	6.4			1.6	503
T: No. of Obs.	4											
Mean	3612											
Min.	3560											
Max.	4160											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT	BOD			Ret	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	MLVSS	SA	SVI	Sl %	DT hrs	SSR gpd/sf
15. Apr.7-9,1969 -- C												
N: No. of Obs.	3	8	3	3	2	3	3	3	3	3	3	3
Mean	2933	4.3	2628	1790	2.14	10.3	0.24	6.1	291	66	2.0	355
Min.	2900	3.9	2406	1658		10.1	0.23	5.6	208	62	1.9	351
Max.	3000	5.2	2896	1936		10.4	0.26	6.5	324	75	2.0	363
D: No. of Obs.	3	2	2	2		3	2	2		1	3	3
Mean	583	0.7	1921	1289		1.7	0.34	4.5		30	1.7	426
Min.	550	0.7	1858	1232		1.6	0.30	4.0			1.6	421
Max.	620	0.7	1994	1336		1.7	0.38	5.0			1.7	430
T: No. of Obs.	3											
Mean	3516											
Min.	3480											
Max	3550											
16. May 12 - 15, 1969 -- C												
N: No. of Obs.	4	12	4	4	3	4	4	4	4	4	4	4
Mean	3325	5.3	5063	3372	2.20	9.1	0.15	10.1	175	78	1.7	402
Min.	3250	2.5	4863	3272		8.9	0.14	9.6	170	74	1.7	393
Max.	3400	7.9	5218	3464		9.3	0.15	11.0	182	81	1.8	412
D: No. of Obs.	4	3	4	4		4	4	4		1	4	4
Mean	623	0.4	2352	1610		1.5	0.30	5.2		25	1.5	478
Min.	530	0.3	2310	1578		1.4	0.23	4.7			1.4	469
Max.	670	0.5				1.5	0.31	6.2			1.5	473
T: No. of Obs.	4											
Mean	3948											
Min.	3910											
Max.	4030											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT				Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	BOD/MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
17. May 19-26,1969 -- C												
N: No. of Obs.	8	4	6	6	6	8	6	6	6	8	8	8
Mean	3900	3.0	4258	2909	2.13	7.7	0.19	7.6	184	68	1.5	476
Min.	3760	0.6	4138	2812		6.7	0.16	6.6	160	59	1.3	455
Max.	4500	4.8	4556	3132		8.0	0.22	9.3	196	73	1.5	545
D: No. of Obs.	7	4	5	5		7	5	5		1	7	7
Mean	750	0.3	1717	1176		1.3	0.47	3.3		23	1.3	561
Min.	690	0.1	1442	1012		1.1	0.30	2.5			1.1	536
Max.	800	0.6	2082	1434		1.3	0.54	4.9			1.3	640
T: No. of Obs.	7											
Mean	4638											
Min.	4430											
Max	5290											
18. May 27 - July 22, 1968 -- V												
N: No. of Obs.	49	24	33	33	6	49	31	32	27	43	49	49
Mean	3634	3.2	4326	3034	2.75	8.3	0.17	8.5	99	58	1.6	439
Min.	3230	0.3	3388	2372		7.7	0.14	5.1	70	43	1.5	412
Max.	4100	6.9	4980	3568		8.9	0.28	11.9	131	72	1.7	496
D: No. of Obs.	49	6	30	30		49	29	29		16	49	49
Mean	824	0.3	1715	1210		1.3	0.53	2.9		23	1.3	529
Min.	310	0.2	378	298			0.32	0.6		11	1.2	490
Max.	940	0.4	2396	1634			2.14	4.7		31	1.4	640
T: No. of Obs.	49											
Mean	4462											
Min.	3710											
Max.	4890											

Table 12

DEMONSTRATION PLANT OPERATIONAL DATA

	Reactor											
	Flow	Mixed Liquor mg/l			Air	DT				Ret Sl	Sed Tank	
	ml/min	DO	SS	VSS	cfm	hrs	BOD/MLVSS	SA	SVI	%	DT hrs	SSR gpd/sf
19. July 24-Aug.21,1969 -- C												
N: No. of Obs.	29	6	21	21	5	29	32	21	20	28	29	29
Mean	2950	3.8	4020	2796	2.30	8.7	0.18	7.8	97	59	2.0	357
Min.	2640	0.8	2192	1526		6.4	0.12	4.5	61	27	1.5	315
Max.	3980	6.3	5612	3896		9.8	0.32	11.9	182	94	2.2	494
D: No. of Obs.	29		21	21		29	21	21	8	28	29	29
Mean	782		1943	1386		1.6	0.65	2.2	397	33	1.6	452
Min.	660		356	274		1.2	0.34	0.3	106	11	1.2	394
Max.	1080		3514	2432		1.8	4.60	4.3	886	49	1.8	615
T: No. of Obs.	29											
Mean	3732											
Min.	3250											
Max	5080											
July 24- Aug. 21, 1969 -- C												
N: No. of Obs.	29	3	20	20	4	29	20	20	19	29	29	29
Mean	3732	4.4	2547	1741	0.63	1.6	0.32	4.6	121	30	1.6	452
Min.	3250	1.2	656	468	0.50	1.2	0.10	1.3	46	21	1.2	394
Max.	5080	6.2	4928	3330	0.81	1.8	1.06	9.6	320	40	1.8	615
D: No. of Obs.	29		21	21		29	21	21	16	29	29	29
Mean	253		2020	1405		1.5	0.25	5.8	318	25	1.5	482
Min.	200		594	400		1.1	0.11	1.2	179	19	1.1	431
Max.	370		4084	2802		1.7	1.38	13.9	785	28	1.7	659
T: No. of Obs.	29											
Mean	3986											
Min.	3450											
Max.	5450											

Analytical data for the demonstration plant are presented in Table 13 and includes mean, minimum, and maximum values. Temperature of the raw flow and mixed liquor are given in degrees centigrade and effluent concentrations in milligrams per litre (mg/l). Concentrations included total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), total phosphorus (TP), 5-day 20°C biochemical oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO).

Table 14 has been prepared to show additional characteristics of denitrification. The feed characteristics have been taken from Table 13 and the Reaction Tank loading values from Table 12. The nitrate reduction rate is given as the milligrams of nitrate-N lost per gram of MLSS per hour. In the ratio of BOD/Nitrate-N the BOD is the 5-day BOD of that portion of the raw waste applied directly to the reaction tank. The Nitrate-N value is either the amount applied or removed (as indicated) in the reaction tank, and the respective ratios are shown as BOD/NA and BOD/N.

Table 15 is a comparison of the expected ammonia and organic nitrogen concentrations in the effluent which originated in the primary feed compared with the actual concentrations. Expected values have been computed as the diluted concentrations from the portion of the primary effluent fed to the denitrification tank.

Throughout the tests the ammonia nitrogen concentration in the primary effluent feed to the units was relatively low and ranged from 3-20 mg/l. Because the objective of the tests was primarily a study of denitrification, no attempt was made to optimize the nitrification process. Consequently to assure good nitrification relatively low loading rates were used in the first stage. Dissolved oxygen concentrations in the denitrification effluent are not very meaningful because of the questionable reliability of the meter used although there may have been slight amounts of

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO		
1. Nov. 1-7, 1968	-- C										
P: No. of Obs.	5			6	6		7				
Mean	19.6			13.5	0.4		182				
Min.	19.0			11.0	0.3		155				
Max.	20.0			19.2	0.7		190				
N: No. of Obs.				5	6						
Mean				0.8	12.5						
Min.				0.7	11.2						
Max.				1.3	14.0						
D: No. of Obs.				5	6				3		
Mean				3.2	2.0				0.7		
Min.				2.3	0,3				0.4		
Max.				4.7	3.2				1.2		
2. Nov. 9-14, 1968	-- C										
P: No. of Obs.	5			4	4		6				
Mean	19.1			10.3	0.4		200				
Min.	19.0			7.0	0.3		150				
Max.	19.5			13.6	0.4		240				
N: No. of Obs.				4	4						
Mean				1.0	12.5						
Min.				0.8	11.0						
Max.				1.2	14.8						
D: No. of Obs.				4	4				4		
Mean				4.1	0.2				0.8		
Min.				3.0	0.1				0.6		
Max.				5.6	0.4				1.0		

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO		
3. Nov. 17-21, 1968 -- C											
P: No. of Obs.	2			3	3	3	5				
Mean	18.4			11.5	0.5	3.2	196				
Min.	18.0			10.0	0.5	3.2	188				
Max.	18.8			12.4	0.5	3.3	230				
N: No. of Obs.		3	1	3	5	3	1	1			
Mean		19.2	3.7	1.1	11.0	1.8	17	70			
Min.		16.8		1.0	10.0	1.6					
Max.		19.5		1.2	12.0	2.1					
D: No. of Obs.			1	3	4	3	1	1	3		
Mean			6.7	2.7	0.4	1.9	11	43	0.8		
Min.				2.5	0.2	1.8			0.7		
Max.				2.8	0.7	2.0			0.9		
4. Nov. 22-Dec. 1, 1968 -- V											
P: No. of Obs.				3	3		10				
Mean				9.7	0.5		212				
Min.				8.0	0.3		175				
Max.				14.8	0.7		220				
N: No. of Obs.		4		3	3		1				
Mean		18.2		1.8	7.6		9				
Min.		17.0		0.7	2.7						
Max.		19.3		4.0	9.8						
D: No. of Obs.				3	3		1		2		
Mean				4.5	1.1		24		0.8		
Min.				2.4	0.7				0.5		
Max.				8.5	1.7				1.0		

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l						
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO
5. Dec. 6-11, 1968 -- V									
P: No. of Obs.	2		1	3	3	1	6		
Mean	16.3		23.2	12.7	0.5	4.6	218		
Min.	15.7			11.0	0.3		165		
Max.	16.8			15.2	0.6		235		
N: No. of Obs.		3	1	3	4	1	1	1	
Mean		17.6	3.1	0.9	11.7	3.3	13	94	
Min.		17.1		0.8	9.0				
Max.		17.9		1.0	14.8				
D: No. of Obs.			1	3	4	1	1	1	3
Mean			4.6	3.5	1.3	3.8	8	88	0.7
Min.				2.5	0.6				0.5
Max.				4.5	2.5				1.2
6. Dec. 12-18, 1968 -- V									
P: No. of Obs.	3			1	2		7		
Mean	15.8			10.0	0.3		205		
Min.	15.5				0.2		175		
Max.	16.0				0.4		230		
N: No. of Obs.		3		2	4				
Mean		16.8		2.2	4.7				
Min.		16.1		0.8	3.3				
Max.		17.5		3.5	8.5				
D: No. of Obs.				2	3				1
Mean				3.9	0.8				0.4
Min.				2.8	0.3				
Max.				5.0	1.7				

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO		
7.Dec.31,1968-Jan, 5,1969 -- V											
P: No. of Obs.	4			2	2		6				
Mean	12.8			13.4	0.4		170				
Min.	11.5			8.8	0.3		115				
Max.	13.8			18.0	0.4		185				
N: No. of Obs.		2		2	2						
Mean		14.5		1.1	10.3						
Min.		13.8		0.9	5.6						
Max.		15.2		1.2	15.0						
D: No. of Obs.				2	2				2		
Mean				3.5	1.5				0.9		
Min.				2.7	0.3				0.9		
Max.				4.2	2.6				0.9		
*8 Jan. 6-9, 1969 -- V											
P: No. of Obs.	1	2		1	1		4				
Mean	12.8			19.6	0.5		220				
Min.							215				
Max.							230				
N: No. of Obs.		4		1	1						
Mean		15.0		1.0	9.6						
Min.		14.3									
Max.		15.5									
D: No. of Obs.				1	1				2		
Mean				5.1	0.6				0.5		
Min.									0.4		
Max.									0.6		

* Samples taken every 2 hours for certain 24-hour periods.

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l					
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD
9. Jan. 10-19, 1969 -- V								
P: No. of Obs.	2		1	1	1	1	10	1
Mean	13.4		22.0	16.4	0.5	5.3	212	442
Min.	13.0						165	
Max.	13.7						245	
N: No. of Obs.		2	1	2	2	1		1
Mean		14.8	2.8	0.9	9.5	3.6		79
Min.		14.3		0.8	6.4			
Max.		15.2		0.9	12.6			
D: No. of Obs.			1	2	2	1		1
Mean			5.5	4.2	0.4	3.9		108
Min.				3.6	0.3			
Max.				4.7	0.4			
10. Jan. 20-29, 1969 -- V								
P: No. of Obs.	3		1	3	3		10	1
Mean	13.8		24.6	14.1	0.4		210	452
Min.	13.0			11.2	0.3		175	
Max.	14.5			16.4	0.5		215	
N: No. of Obs.		2	1	5	5		1	1
Mean		14.8	2.5	2.1	8.0		16	88
Min.		14.0		0.2	6.0			
Max.		15.5		5.3	9.6			
D: No. of Obs.			1	6	6		1	1
Mean			4.6	3.0	0.7		20	94
Min.				0.3	0.3			
Max.				8.5	1.5			

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO		
11. Feb.24-Mar.8,'69 -- C											
P: No. of Obs.	9			9	9		13				
Mean	13.7			13.2	0.5		216				
Min.	12.5			11.0	0.3		165				
Max.	14.5			16.6	0.6		235				
N: No. of Obs.		10		9	9						
Mean		14.6		2.6	3.3						
Min.		13.0		1.3	2.3						
Max.		15.7		7.2	4.5						
D: No. of Obs.				10	10				7		
Mean				3.3	0.6				0.5		
Min.				1.3	0.2				0.4		
Max.				7.9	1.6				0.6		
12. Mar. 19-26, 1969 -- C											
P: No. of Obs.	6			6	6		8				
Mean	11.7			8.2	0.6		177				
Min.	7.5			5.6	0.4		120				
Max.	13.0			9.9	0.7		195				
N: No. of Obs.		6		6	6		1				
Mean		12.9		1.7	8.3		24				
Min.		11.0		1.2	7.2						
Max.		13.6		2.2	9.8						
D: No. of Obs.				6	6		1		6		
Mean				1.9	3.2		13		2.2		
Min.				1.7	0.4				1.6		
Max.				2.8	5.4				3.1		

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO		
13.Mar.27-29, 1969 -- V											
P: No. of Obs.	2		1	1	1		3	1			
Mean	10.1		20.9	10.8	0.7		165	372			
Min.	9.2						150				
Max.	11.0						185				
N: No. of Obs.		2	1	1	1		1				
Mean		13.3	5.5	2.7	6.5		18				
Min.		12.5									
Max.		14.0									
D: No. of Obs.			1	1	1		1	1	1		
Mean			8.9	3.3	0.7		35	162	0.9		
Min.											
Max.											
14. Mar.31 - Apr. 3, 1969 -- C											
P: No. of Obs.	4			4	4		4				
Mean	12.1			7.6	0.4		193				
Min.	10			2.6	0.3		190				
Max.	13.5			12.0	0.5		195				
N: No. of Obs.		4		4	4						
Mean		13.4		1.1	8.7						
Min.		10.7		0.5	7.3						
Max.		15.7		1.6	10.8						
D: No. of Obs.				4	4						
Mean				1.7	2.4						
Min.				0.7	0.4						
Max.				2.7	4.2						

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
*	Raw	ML	TKN	NH$_3$-N	NO$_3$-N	TP	BOD	COD	DO		
15. Apr.7-9, 1969	-- C										
P: No. of Obs.	3			3	3		3				
Mean	15.3			12.7	0.4		185				
Min.	15.0			11.2	0.3		180				
Max.	15.5			14.0	0.4		195				
N: No. of Obs.		2		3	3						
Mean		16.0		1.4	13.3						
Min.		15.0		1.4	10.8						
Max.		16.5		1.5	15.3						
D: No. of Obs.				3	3				3		
Mean				2.8	5.1				0.6		
Min.				2.5	1.7				0.2		
Max.				3.2	8.2				1.0		
16. May 12-15, 1969 -- C											
P: No. of Obs.	3			3	3		4				
Mean	17.6			13.3	0.6		192				
Min.	16.8			13.1	0.4		185				
Max.	19.0			14.2	0.7		195				
N: No. of Obs.		3		4	4						
Mean		18.0		1.2	10.1						
Min.		17.0		1.0	8.4						
Max.		18.9		1.4	11.0						
D: No. of Obs.				4	4				3		
Mean				2.8	1.1				0.7		
Min.				2.5	0.6				0.4		
Max.				3.1	2.0				0.9		

* Samples taken every 2 hours for certain 24-hour periods.

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °C		Effluent Concentrations, mg/l					
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD
*17. May 19-26, 1969 -- C								
P: No. of Obs.	4		1	3	3		8	
Mean	18.3		18.9	13.2	0.6		172	
Min.	18.0			10.3	0.5		165	
Max.	19.0			16.4	0.7		205	
N: No. of Obs.		5	1	4	4			
Mean		17.6	3.2	1.2	10.9			
Min.		17.2		0.8	9.0			
Max.		18.2		1.3	13.8			
D: No. of Obs.			1	4	4			
Mean			4.0	2.4	3.7			
Min.				1.0	1.1			
Max.				3.1	8.4			
*18. May 27-July 22, 1969 -- V								
P: No. of Obs.	32		2	28	29		57	
Mean	20.7		19.3	11.8	0.6		175	
Min.	17.4		19.2	8.0	0.4		125	
Max.	24.0		19.4	16.5	0.8		215	
N: No. of Obs.		6	2	32	33		4	1
Mean		20.8	3.0	2.0	9.9		20	125
Min.		18.0	2.7	0.3	0.5		13	
Max.		23.8	3.3	6.2	17.4		29	
D: No. of Obs.			2	29	34		4	1
Mean			4.2	3.2	2.4		19	110
Min.			3.4	1.3	0.3		16	
Max.			5.0	4.1	5.5		22	

* Samples taken every 2 hours for certain 24-hour periods.

Table 13

DEMONSTRATION PLANT ANALYTICAL DATA

	Temp, °c		Effluent Concentrations, mg/l								
	Raw	ML	TKN	NH_3-N	NO_3-N	TP	BOD	COD	DO	SS	VSS
19. July 24-Aug.21,1969--C											
P: No. of Obs.	17		1	21		1	27	1		1	1
Mean	22.6		26.5	11.7		9.2	163	482		255	187
Min.	21.5			9.2			130				
Max.	23.5			16.2			195				
N: No. of Obs.			1	21	21	1		1	3	1	1
Mean			3.5	2.7	7.8	5.2		132	3.8	55	48
Min.				0.9	4.2				3.3		
Max.				9.0	13.8				4.4		
D: No. of Obs.				21	21	1		1		1	1
Mean				3.9	0.5	5.8		153		49	41
Min.				2.7	0.2						
Max.				9.8	2.9						
July 24 - Aug. 21, 1969 -- C											
P: No. of Obs.											
Mean											
Min.											
Max.											
N: No. of Obs.			1	21	21	1		1	3	1	1
Mean			1.1	1.7	4.3	5.4		72	4.4	20	18
Min.				0.8	0.5				1.2		
Max.				7.8	9.3				6.2		
D: No. of Obs.			1	21	21	1		1		1	1
Mean			2.5	1.8	0.8	6.1		76		39	27
Min.				0.9	0.3						
Max.				2.6	2.1						

Table 14. Demonstration Plant Denitrification Test Data

Test No.	Feed Nitrate mg/l N	Feed BOD mg/l	Reaction Tank			
			Loading BOD/MLVSS	Nitrate reduction rate mg N/g MLSS/hr	BOD/Nitrate-N Ratio	
					N-Applied BOD/NA	N-Removed BOD/N
1	12.5	182	0.56	3.72	3.62	*4.31
2	12.5	200	0.60	2.73	5.12	5.21
3	11.0	196	0.72	4.16	4.68	4.86
4	7.6	212	1.10	2.97	6.90	*8.06
5	11.7	218	0.47	2.75	4.85	*5.43
6	4.7	205	0.45	0.89	11.50	13.90
7	10.3	170	0.16	1.64	3.30	*3.87
8	9.6	220	-	1.22	4.71	5.02
9	9.5	212	0.35	1.97	5.35	5.59
10	8.0	210	0.28	1.89	3.27	3.58
11	3.3	216	0.39	1.51	4.85	5.93
12	8.3	177	0.28	1.30	3.63	*5.91
13	6.5	165	0.16	0.93	3.97	4.44
14	6.3	193	0.28	1.44	3.71	*4.86
15	13.3	185	0.34	2.09	2.49	*4.04
16	10.1	192	0.30	2.15	3.20	*3.58
17	10.9	172	0.47	2.71	2.68	*4.06
18	9.9	175	0.53	2.74	3.62	*4.77
19_1	7.8	163	0.65	1.86	5.07	5.41
19_2	4.3	163	0.25	1.08	1.71	(2.09)

* Partial denitrification

Table 15. Demonstration Plant Effluent Ammonia and Organic Nitrogen

Test No	Nitrification effluent NH_3-N mg/l	Denitrification Effluent, mg/l			
		Expected Proportionate concentrations		Actual concentrations	
		NH_3-N	TKN	NH_3-N	TKN
1c	0.8	2.9		3.2	
2c	1.0	2.6		4.1	
3c	1.1	2.5		2.7	6.7
4v	1.8	2.0		4.5	
5v	0.9	2.8	5.2	3.5	4.6
6v	2.2	2.2		3.9	
7v	1.1	2.4		3.5	
8v	1.0	3.6		5.1	
9v	0.9	3.4	4.5	4.2	5.5
10v	2.1	1.8	3.1	3.0	4.6
11c	2.6	1.1		3.3	
12c	1.7	1.2		1.9	
13v	2.7	1.6	3.2	3.3	8.9
14c	1.1	1.2		1.7	
15c	1.4	2.1		2.8	
16c	1.2	2.1		2.8	
17c	1.2	2.1	3.1	2.4	4.0
18v	2.0	2.2	3.6	3.2	4.2
19_1c	2.7	2.5		2.7	
19_2c	1.7	0.7	1.7	1.8	2.5

oxygen introduced into the denitrification reaction tank. Initially with the gas recirculation mixing the tank seal may not have been tight and some air may have been introduced by the recirculation of these gases. Later, the degasifer may have provided some oxygen and also the mechanical mixer used instead of gas recirculation may have introduced some oxygen.

2. Test 1

This test period was the first during which meaningful data were obtained, and there was good nitrification but only partial denitrification. Reasonable rates of nitrate reduction were obtained. The BOD/N ratios were close to optimum. The best measures of optimum BOD/N ratios should be when only partial denitrification is achieved. In Table 15 it is evident that the effluent ammonia nitrogen was essentially that from the primary feed to the denitrification tank.

3. Test 2

More complete denitrification was obtained in Test 2 by reason of a higher BOD/NA ratio. Very likely an excess of BOD was being used.

4. Test 3

Reasonably good nitrification and excellent denitrification were achieved. Probably a slight excess of BOD was applied to the denitrifying unit when comparing the BOD/N ratio with that of Test 1. The TKN value in the effluent was particularly high due in part to the effluent SS. The final effluent BOD was excellent at only 11 mg/l.

5. Test 4

The ammonia nitrogen concentration in the feed was particularly low in this test and only partial nitrification and denitrification was achieved. Although high BOD/N ratios should surely result in complete denitrification such was not the case in this test and no explanation is evident. Variable flow was first introduced with this test and the flow variations were similar to those shown in Figure 19. The maximum flow to the nitrification unit occured approximately 4 hours after the maximum flow to the primary unit.

6. Test 5

Nitrification was quite complete but the sludge was becoming less settleable as evidenced by the rise in the SVI. The rising SVI coincides with the lowering of the temperature of the incoming waste. Only reasonably good denitrification was obtained despite the higher BOD/N ratios.

7. Test 6

Nitrification was incomplete but denitrification was quite good. Particularly high BOD/N ratios were used and consequently denitrification should be quite complete. Again the SVI in the nitrification process was shown to be increasing.

8. Test 7

Neither nitrification nor denitrification were quite complete but were reasonably good. Ratios of BOD/N were the lowest obtained to date and indicated optimum values of less than 4.0. During this test the mechanical mixer was substituted for gas recirculation in the denitrification tank.

9. Test 8

Despite the short duration of the test and minimal data, the results were good in that good nitrification and denitrification were achieved. The BOD/N ratios used, however, were quite high. Although the raw waste temperature dropped to 12.8°C in this test and Test 7 there was not a corresponding rise in the SVI.

10. Test 9

Low raw waste temperatures prevailed during this test and a rise in the SVI was observed. Good nitrification and denitrification was obtained but a rather high BOD/N ratio was used.

11. Test 10

Nitrification in this test was marginal but denitrification was quite complete. One of the minimum BOD/N ratios was used for this test and may be considered optimum (3.58).

12. Test 11

Generally speaking the highest SVI values were found during this test and the subsequent tests numbered 12, 13 and 14. Coincidentally the temperatures of the raw waste were the lowest during this period as well with values as low as 7.5°C. (Probably due to ice melts). Again nitrification was incomplete but denitrification was quite good as expected with the rather high BOD/N ratios. Constant flow was again used and the results seem to be little influenced by the flow conditions. Incomplete nitrification may have been due to the high loading rates on the aeration tank; the aeration tank was operated with the highest BOD/MLVSS ratio and lowest DT of any test. Similarly, the denitrification reation tank was operated with a mean detention time of only 1.3 hrs, the minimum used in any test.

13. Test 12

Nitrification was somewhat improved over Test 11 but denitrification was incomplete despite a rather high BOD/N ratio. A low effluent BOD was observed.

14. Test 13

This test was quite short and only a minimum of data were taken. Nitrification was not complete but denitrification was good. The BOD of the nitrification unit was good at 18 mg/l but that of denitrification was rather high at 35 mg/l and very likely due to high SS in the effluent. Reasonably low BOD/N ratios were used. Variable flow was used and low temperatures were encountered.

15. Test 14

Because of the high SVI and tendency for solids loss the flow was changed to a constant rate. Reasonably good nitrification was achieved but only partial denitrification in spite of a reasonably high BOD/N ratio. Very low ammonia nitrogen concentrations were found in the raw waste.

16. Test 15

These data were the last obtained prior to shut-down due to high-water conditions in the Mississippi River, the receiving waters for the MSSD plant. Reasonably good nitrification but only partial denitrification was obtained. A fairly low BOD/N ratio of 4.04 was used. Raw waste temperatures were higher than encountered in previous tests.

17. Test 16

After the shut-down period and a period of start-up data were again taken for Test 16. Both nitrification and denitrification were quite good and the minimum BOD/N ratio of 3.58 was used. Constant flow was used.

18. Test 17

The constant flow conditions were continued and the minimum mean holding time in the denitrification tank of 1.3 hours was used. Quite good nitrification was obtained but only partial denitrification was found. This is evident from the low BOD/NA ratio used. The BOD/N ratio was close to that considered optimum. Next to the lowest nitrification DT was used, that being 7.7 hrs. The BOD/MLVSS ratio, however, was quite low.

19. Test 18

Variable flow was again used and raw waste temperatures were again over 20°C. This test period was of 57 days duration and was the longest of any period analyzed. Nitrification was not complete and may be due to the variable flow imposed on the system. A reasonable aeration tank holding time of 8.3 hours was used together with a low BOD/MLVSS ratio. Denitrification was not complete and was probably due to the marginal BOD/NA ratio used. The BOD/NA ratio was higher than considered optimum. Several effluent BOD's were taken and both nitrification and denitrification units had average BOD's of 20 mg/l or less. Denitrification was accomplished in a minimum holding time of 1.3 hours.

20. Test 19

The last test period was for 29 days and involved a four stage process. The process was conducted at constant flow rates. For the first two stages nitrification was not complete but denitrification was very complete. The latter was expected being that high BOD/NA ratios were used.

In the last two stages nitrification again was not quite complete but the denitrification was. Extremely low BOD/NA ratios were used and accomplished the desired denitrifications.

21. Discussion of Test Results

a. Overall

Overall, the data show that nitrogen removal from a municipal wastewater by the denitrification process is possible. Although in these particular tests the ammonia and organic nitrogen concentrations in the primary effluent were rather low the results of the tests should be applicable, where higher nitrogen concentrations prevail.

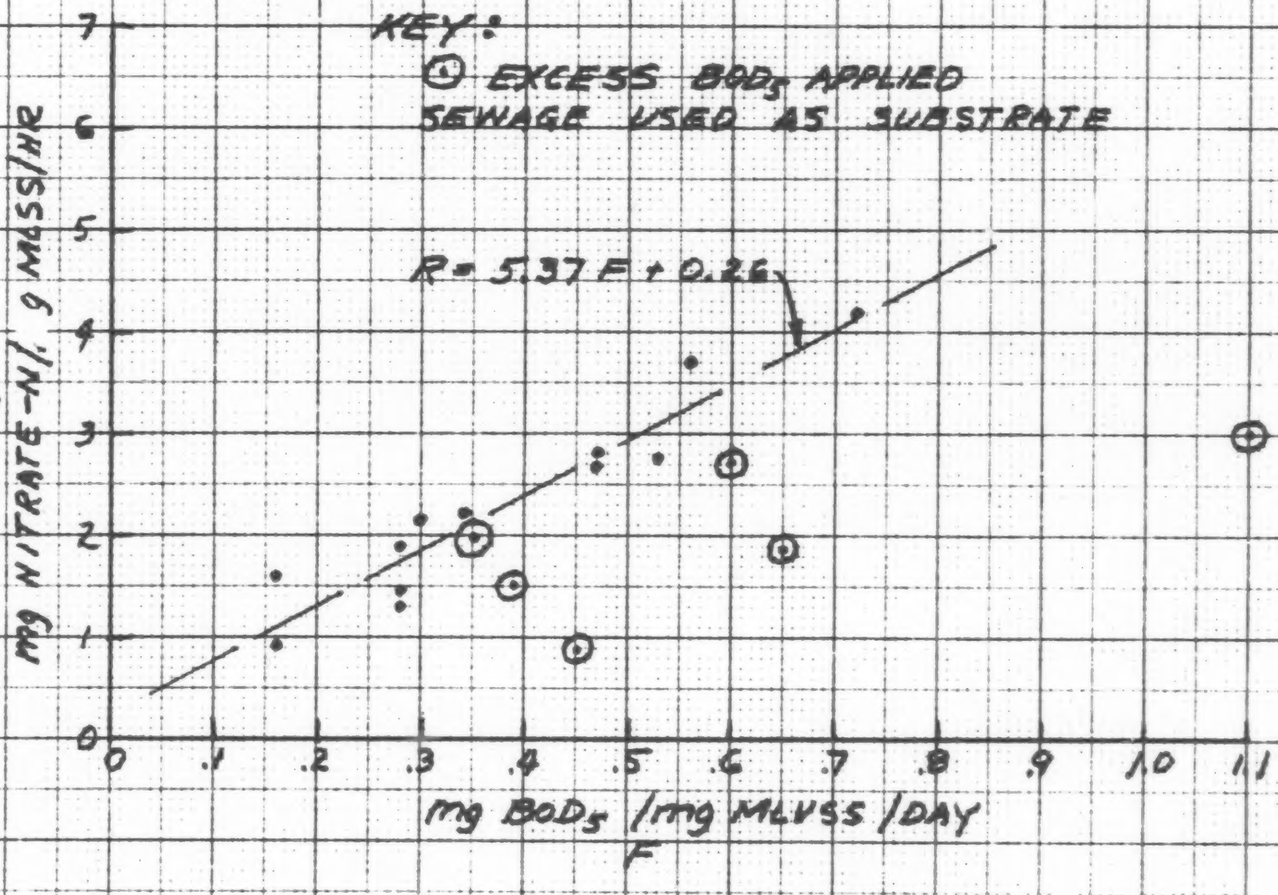
b. Nitrification

As mentioned previously, optimization of the nitrification process was not the objective of these tests and consequently very conservative operation was used to assure reasonably complete nitrification. In these tests nitrification was accomplished within the BOD/MLVSS ratio limits previously specified and the minimum mean aeration tank holding time used was 8.3 hours. Evidence of poor settleability of the sludge at low temperature was shown by the high SVI values observed at these conditions. Although high SVI values correlated with low temperatures it is believed that temperature is a contributory but not sole cause of sludge bulking. Although the effect of temperature on nitrification was not thoroughly examined, reasonably complete nitrification was maintained with aeration periods of 8.7 hours with mean temperatures as low as 12°C. As shown in Table 15, the ammonia nitrogen residual from the nitrification process was seldom less than 1.0 mg/1 and the highest mean value was 2.7 mg/1. There is some indication from the data shown that variable flow may yield somewhat higher residuals than constant flow rates. Nevertheless it is believed that consistent concentrations of less than 1.0 mg/1 may be obtained with better operating conditions. Satisfactory effluent BOD's were evident.

c. Denitrification

Reasonably complete denitrification was obtained with these less than ideal operating conditions. Holding times in the reaction tank of 1.3 hours were satisfactory to accomplish denitrification and probably even shorter detention times could be used. The variable flow conditions imposed on the process did not seem to have had an appreciable effect on the effluent as compared to using constant flow rates. Although effluent BOD's were generally satisfactory at less than 20 mg/1 it is believed that the high effluent SS concentrations could be reduced with a better designed final settling tank. The residual nitrogen from the denitrification process under optimum conditions consisted of less than 1.0 mg/1 nitrate nitrogen together with some ammonia and organic forms. Most of the organic nitrogen was associated with the effluent suspended solids and the ammonia was largely from the primary effluent added to the process as the carbon source. In Table 15 the expected Proportionate Concentrations of NH_3-N and TKN were computed as the respective amounts in the primary feed to the denitrification unit diluted into the entire flow. It is evident that these NH_3-N values were consistently and slightly less than the actual NH_3-N concentrations found by test. Such a difference is expected in view of the conversion of some of the organic-N from the primary feed to the NH_3-N form during processing. The conclusion to be drawn is that the effluent nitrogen is primarily a function of the additional unoxidized nitrogen forms added to the process when supplying the carbon source. The use of a carbon source devoid of nitrogen would thereby eliminate most of the nitrogen from the effluent.

Important characteristics of the denitrification process are presented in Table 14 and Figure 18. The relatively low feed nitrate concentrations were expected because of the low nitrogen concentrations in the raw waste. The organic loading ratios (BOD/MLVSS) have been plotted against the rates of nitrate reduction in terms of mg nitrate-nitrogen removed/g MLSS/hr and presented in Figure 18. The data in Figure 18 show a relationship between the rate of nitrate reduction and the organic loading ratio. By recognizing the need to maintain a reasonably constant ratio between the BOD of the carbon source and the substrate to be reduced, the more meaningful data should be those where only partial denitrification was achieved. The application of high ratios would achieve denitrification but would mean an excessive use of the carbon source and would not indicate an optimum and minimum ratio. The circled data designate those conditions when



NITRATE REDUCTION RATES IN DEMONSTRATION PLANT TESTS

FIGURE 18

known excesses of substrate were used and were not used in the calculation of the regression line for the plot. The relationship between R and F was found to be:

$$R = 5.37F + 0.26$$

and the correlation coefficient was 0.95.

The linear relationship clearly show the dependence of R on F and that a constant BOD/N ratio should be used to achieve complete denitrification. It is again noted that the optimum BOD/N ratio may not be obtained directly from this graph because of methods of averaging and that the BOD available for nitrate reduction has been computed with an allowance for oxygen entrained in the denitrification reactor.

d. Two-Stage Operation

The operation of the two stage plant utilizing two nitrification processes and two denitrification processes was operable and did result in decreasing nitrogen concentrations through the service of units. Approximately 90% removal of nitrogen was achieved. It is recognized, however, that such a process is very likely far more costly than to use one stage with an external carbon source.

22. Process variations over 24-hour periods

a. Sampling

For selected days samples were taken every two hours and analyzed primarily for ammonia and nitrate nitrogen, but on occasion samples were also analyzed for phosphorus, COD and TOC (total organic carbon). All of the data collected are presented in Tables 16-21 and Figures 19-42. The tests considered most reliable in so far as the operating conditions and sampling problems were concerned were those for June 5-6, June 17-18, June 19-20, and July 10-11, 1969. For these dates load curves have been constructed which combine the flow and concentration to give mass flows. The data are

Table 16

DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l								
	Flow Rates, ml/min			Primary			Nitrification			Denitrification		
Time	Prim-N	Prim-D	Total	NH_3-N	NO_3-N	TP	NH_3-N	NO_3-N	TP	NH_3-N	NO_3-N	TP
January 6-7, 1969												
9:30 am	2800	450	3250	16.4	0.1					4.8	0.5	
11:00 am	3400	500	3900	18.0	0.2					3.8	0.5	
1:00 pm	3800	600	4400	18.0	0.2					3.0	0.7	
3:00	4100	800	4900	17.0	0.3					3.2	1.0	
5:00	4100	1000	5100	17.2	0.3					4.0	0.8	
7:00	3700	1200	4900	16:0	0.3					4.1	1.2	
9:00	3150	1150	4300	16.2	0.3					4.8	0.9	
11:00	2500	1000	3500	15.8	0.4					5.3	0.3	
1:00 am	1850	750	2600	16.0	0.4					5.3	0.3	
3:00	1500	550	2050	15.6	0.5					5.9	0.8	
5:00	1600	450	2050	15.0	0.7					5.1	0.5	
7:00	2150	450	2600	14.4	0.5					-	0.2	
January 7-8, 1969												
9:30 am	2800	450	3250	12.2	0.5	5.4	1.2	7.8	5.6	4.2	0.3	6.3
11:00	3500	500	4000	16.4	0.6	5.4	1.2	7.0	5.7	1.9	0.4	5.8
1:00 pm	3900	600	4500	20.8	0.6	5.5	1.4	6.8	5.2	3.4	0.3	5.9
3:00	4150	850	5000	23.2	0.6	5.1	1.7	6.6	4.8	4.1	0.4	4.8
5:00	4100	1100	5200	25.2	0.7	5.4	1.6	6.8	4.5	3.7	0.4	4.5
7:00	3700	1200	4900	19.6	0.6	5.9	1.7	8.0	4.3	5.3	0.4	4.4
9:00	3150	1150	(1150)	20.0	0.6	4.5	2.6	8.2	4.4	4.9	0.4	4.0
11:00	2450	1000	(1000)	16.8	0.6	5.7	2.0	-	4.1	5.9	0.5	4.6
1:00 am	2000	750	(750)	18.4	0.6	5.8	1.6	8.8	4.6	5.7	0.5	5.0
3:00	1550	550	(550)	17.0	0.6	6.2	1.6	9.4	5.5	6.5	0.5	5.6
5:00	1550	450	(450)	16.8	0.6	6.5	2.7	5.8	5.6	5.4	0.5	5.8
7:00	2250	450	(450)	14.8	0.6	5.7	2.7	5.4	5.3	7.4	0.5	6.3
January 8-9, 1969												
9:30 am	2800	450	3250	12.0	0.5		1.2	5.0		7.0	0.4	
11:00	3500	500	4000	14.0	0.6		1.0	6.2		5.4	0.5	
1:00 pm	3900	600	4500	17.2	0.6		1.0	5.4		3.3	0.4	
3:00	4150	850	5000	20.8	0.5		1.5	6.8		3.0	0.4	
5:00	4100	1100	5200	23.2	0.4		2.4	3.0		4.2	0.4	
7:00	3700	1200	4900	21.6	0.5		2.0	3.6		5.5	0.4	
9:00	3150	1150	4300	17.0	0.5		2.5	6.0		6.2	0.4	
11:00	2500	1000	3600	20.8	0.5		2.5	5.6		6.6	0.4	
1:00 am	1850	750	2600	17.2	0.5		1.3	8.6		6.4	0.4	
3:00	1500	550	2050	16.4	0.4		1.3	8.4		6.0	0.4	
5:00	1600	450	2050	16.0	0.5		1.0	8.4		5.5	0.4	
7:00	2150	450	2600	13.2	0.7		1.0	7.4		5.0	0.4	

Table 17

DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l								
	Flow Rates, ml/min			Primary			Nitrification			Denitrification		
Time	Prim-N	Prim-D	Total	NH_3-N	NO_3-N	COD	NH_3-N	NO_3-N	COD	NH_3-N	NO_3-N	COD
April 7-8, 1969												
10:30 am	3000	590	3590	10.8	0.4		2.1	15.6		3.4	8.5	
12:00	"	"	"	13.8	0.4		2.0	14.8		3.7	8.6	
2:00 pm	"	"	"	15.6	0.3		1.5	15.4		3.6	7.3	
4:00	"	"	"	14.2	0.3		1.3	14.8		2.6	6.3	
6:00	"	"	"	14.8	0.3		1.2	14.4		3.5	5.7	
8:00	"	"	"	16.4	0.4		1.5	14.0		3.2	5.5	
10:00	"	"	"	12.2	0.4		1.7	12.8		3.0	5.1	
12:00	"	"	"	12.0	0.4		1.6	12.0		2.7	5.1	
2:00 am	"	"	"	12.6	0.4		1.6	12.6		3.0	4.1	
4:00	"	"	"	12.0	0.5		1.5	12.0		2.8	2.2	
6:00	"	"	"	11.2	0.6		1.5	8.8		2.4	3.1	
8:00	"	"	"	10.4	0.6		1.7	7.0		2.5	2.4	
April 8-9, 1969												
10:00 am	2800	600	3400	12.0	0.5		1.2	7.4		2.5	2.0	
12:00	"	"	"	12.2	0.4		1.2	8.0		2.5	1.1	
2:00 pm	"	"	"	9.2	0.3		1.2	9.2		2.3	1.4	
4:00	"	"	"	10.0	0.3		1.1	9.4		2.4	1.4	
6:00	"	"	"	14.4	0.4		1.1	9.2		2.4	1.1	
8:00	"	"	"	13.8	0.4		1.1	10.0		2.6	0.8	
10:00	"	"	"	14.4	0.4		1.1	8.6		2.5	0.7	
12:00	"	"	"	15.2	0.4		1.2	9.2		2.7	0.8	
2:00 am	"	"	"	15.8	0.5		1.4	9.0		2.7	0.8	
4:00	"	"	"	15.2	0.5		1.6	8.2		2.9	0.7	
6:00	"	"	"	13.8	0.6		2.0	8.0		3.0	0.7	
8:00	"	"	"	12.8	0.6		2.6	7.8		2.8	1.4	
May 21-22, 1969												
10:00 am	3780	750	4530	12.0	0.3	382	1.0	8.3	95	1.8	0.6	93
12:00	"	"	"	14.5	0.7	398	1.0	8.3	82	1.5	0.7	119
2:00 pm	"	"	"	17.1	0.5	335	1.0	8.3	84	1.6	0.6	128
4:00	"	"	"	17.8	0.6	398	0.9	8.8	87	1.5	0.6	130
6:00	"	"	"	17.1	0.5	377	1.0	10.1	89	2.0	0.9	128
8:00	"	"	"	14.3	0.2	366	0.9	11.5	84	1.7	0.6	147
10:00	"	"	"	11.5	0.5	348	0.9	12.2	76	2.2	1.7	112
12:00	"	"	"	10.1	0.6	566	0.9	11.8	72	1.4	1.8	136
2:00 am	"	"	"	11.9	0.7	326	0.8	11.1	84	1.3	2.7	139
4:00	"	"	"	13.7	0.5	346	0.8	10.9	70	1.1	2.2	143
6:00	"	"	"	17.2	0.8	375	0.9	10.6	72	1.8	2.4	239
8:00	"	"	"	15.7	0.8	346	0.8	10.2	68	1.9	2.0	88

Table 18

DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l								
	Flow Rates, ml/min			Primary			Nitrification			Denitrification		
Time	Prim-N	Prim-D	Total	NH_3-N	NO_3-N		NH_3-N	NO_3-N		NH_3-N	NO_3-N	
May 22-23, 1969												
9:30 am	3780	750	4530	10.1	0.6		1.0	10.0		2.3	1.8	
11:30	"	"	"	12.9	0.6		1.0	8.8		2.1	1.5	
1:30 pm	"	"	"	15.4	0.6		1.0	8.6		2.1	3.1	
3:30	"	"	"	16.2	0.6		1.0	8.6		2.2	3.4	
5:30	"	"	"	16.0	0.6		1.1	8.8		2.3	3.1	
7:30	"	"	"	15.7	0.5		1.1	10.2		2.3	4.1	
9:30	"	"	"	16.0	0.6		1.1	9.4		2.1	4.3	
11:30	"	MALFUNCTION		16.0	0.6					2.0	6.2	
1:30 am	"	"	"	14.8	0.6					2.8	5.8	
3:30	"	"	"	15.7	0.6					2.4	5.8	
5:30	"	"	"	14.8	0.6					2.5	5.9	
7:30	"	"	"	14.0	0.6					2.8	5.8	
June 4-5, 1969												
9:30 am	3300	610	3910	11.6			1.4	11.8		2.6	0.5	
11:00	4900	540	5440	13.0			1.3	9.6		1.4	0.4	
1:00 pm	5500	550	6050	15.4			1.3	9.2		1.2	0.9	
3:00	5600	600	6200	15.0			1.4	9.8		1.2	3.5	
5:00	5350	740	6090	15.1			1.3	9.2		1.2	4.9	
7:00	4850	930	5780	14.6			1.3	10.0		1.2	4.5	
9:00	3950	1110	5060	13.7			1.3	8.4		1.3	4.3	
11:00	3150	1190	4340	13.9			1.4	9.0		1.2	4.6	
1:00 am	2700	1140	3840	14.4			1.4	8.8		1.4	2.5	
3:00	2400	970	3370	14.7			1.4	9.6		3.1	0.8	
5:00	2500	850	3350	14.4			1.4	10.2		3.6	0.7	
7:00	2950	730	3680	13.2			1.4	10.0		4.3	0.6	
June 5-6, 1969												
10:30 am	4150	580	4730	10.1			1.0	11.0		1.9	0.8	
12:00	5150	560	5710	13.5			1.0	10.8		1.3	1.8	
2:00 pm	5600	570	6170	16.2			1.0	10.4		1.4	2.7	
4:00	5100	750	5850	15.8			1.0	10.6		1.5	2.8	
6:00	5200	820	6020	16.0			1.0	11.0		1.6	2.9	
8:00	4400	1035	5435	12.8			1.0	11.8		1.7	2.3	
10:00	3600	1170	4770	12.6			1.0	11.8		1.9	2.0	
12:00	2900	1180	4080	13.1			1.0	12.2		2.3	1.1	
2:00 am	2500	1060	3560	12.1			1.0	12.0		2.5	0.7	
4:00	2350	920	3270	12.5			1.0	12.4		3.4	1.0	
6:00	2650	770	3420	12.6			1.1	12.6		3.6	1.0	
8:00	3300	660	3960	11.6			1.2	13.6		3.1	1.0	

Table 19

DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l								
	Flow Rates, ml/min			Primary			Nitrification			Denitrification		
Time	Prim-N	Prim-D	Total	NH_3-N	NO_3-N		NH_3-N	NO_3-N		NH_3-N	NO_3-N	
June 16-17, 1969												
9:30 am	3500	640	4140	11.8			1.8	16.2		2.7	2.1	
11:00	4750	600	5350	12.3			1.6	12.2		1.9	4.0	
1:00 pm	5300	610	5910	12.7			1.4	13.0		1.7	3.1	
3:00	5350	700	6050	13.1			1.3	10.0		1.6	3.8	
5:00	5150	830	5980	13.5			1.0	10.0		1.6	2.7	
7:00	4650	1010	5660	13.1			1.0	10.2		1.8	1.4	
9:00	3850	1220	5070	12.1			1.1	10.0		2.4	0.5	
11:00	3000	1320	4320	12.9			1.2	10.6		3.0	0.4	
1:00 am	2450	1290	3740	12.2			1.2	11.0		3.8	0.3	
3:00	2020	1190	3210	12.9			1.2	11.6		3.8	0.4	
5:00	2200	990	3190	13.2			1.2	12.0		4.2	0.4	
7:00	2750	810	3560	10.0			1.1	12.8		4.7	0.4	
June 17-18, 1969												
10:00 am	3750	650	4400	10.3			1.1	13.4		4.7	0.2	
12:00	4800	600	5400	13.2			1.1	11.8		2.8	0.2	
2:00 pm	5400	620	6020	15.0			1.1	11.2		1.4	0.6	
4:00	5350	680	6030	15.6			0.9	9.8		1.2	1.0	
6:00	5150	800	5950	16.8			1.1	10.2		1.6	0.5	
8:00	4400	960	5360	15.8			1.0	9.2		2.3	0.2	
10:00	3450	1160	4610	14.2			1.2	10.0		2.5	0.2	
12:00	2850	1290	4140	14.4			1.0	10.2		3.2	0.1	
2:00 am	2450	1320	3770	14.3			1.0	11.0		4.0	0.3	
4:00	2200	1220	3420	13.7			1.1	11.2		3.7	0.2	
6:00	2400	1040	3440	12.7			1.0	12.0		3.4	0.4	
8:00	2900	820	3720	10.8			1.1	11.2		4.2	0.3	
June 19-20, 1969												
8:30 am	3100	680	3780	10.0			0.9	9.6		1.1	3.5	
10:00	4250	620	4870	10.8			0.9	8.4		1.4	1.4	
12:00	5100	600	5700	13.6			1.0	8.8		1.3	2.1	
2:00 pm	5600	650	6250	14.4			0.9	7.6		1.3	2.1	
4:00	5550	760	6310	14.8			1.0	6.8		1.2	1.4	
6:00	5250	920	6170	15.2			1.0	7.2		2.0	0.8	
8:00	4650	1130	5780	15.2			0.9	7.8		2.2	0.6	
10:00	3750	1280	5030	15.2			0.9	8.4		2.4	0.6	
12:00	2900	1310	4210	14.4			0.9	10.4		3.0	0.4	
2:00 am	2500	1240	3740	14.8			0.9	10.2		4.1	0.6	
4:00	2400	1070	3470	16.0			0.9	12.0		4.4	0.6	
6:00	2600	870	3470	14.0			0.8	12.6		4.3	0.6	

Table 20

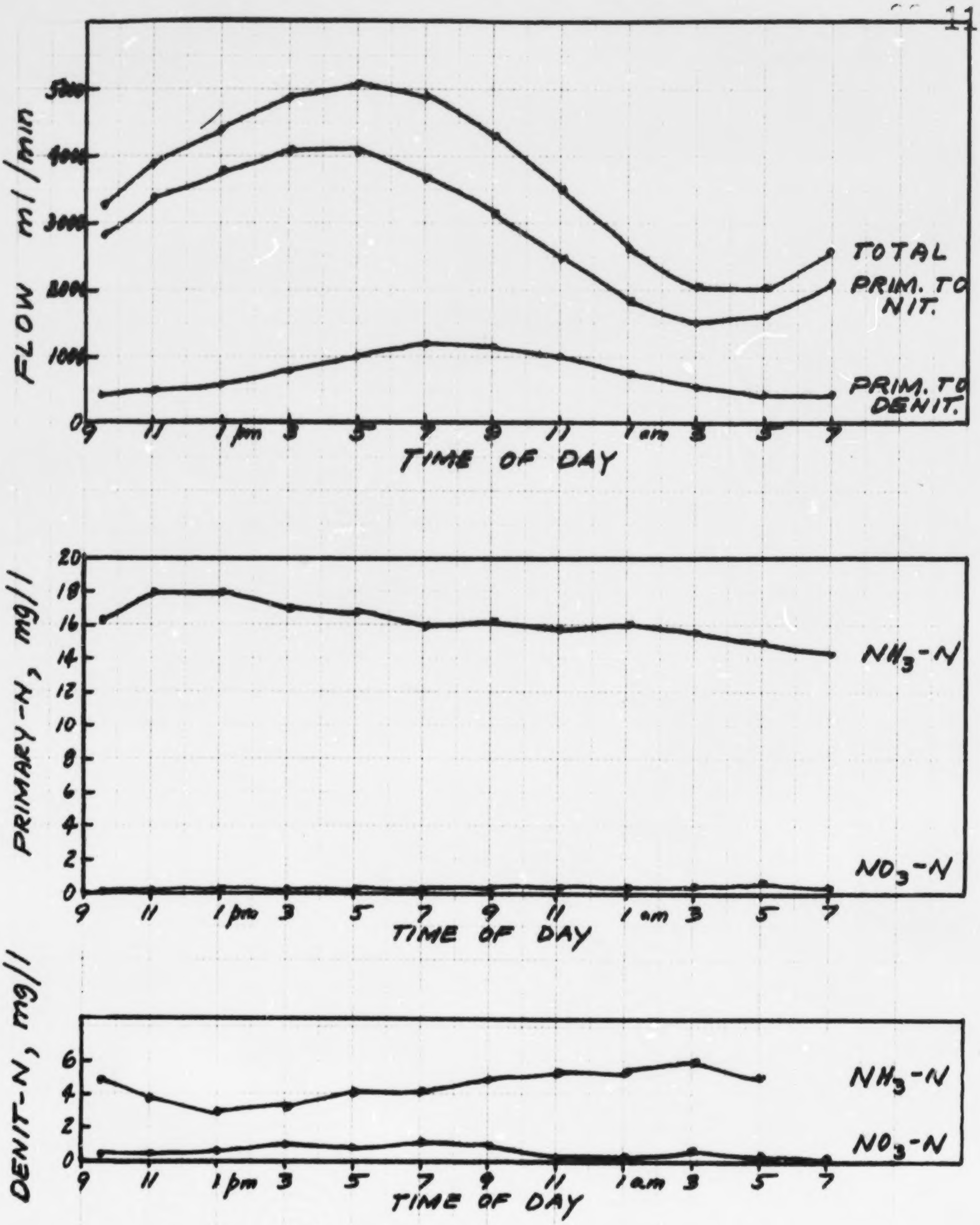
DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l					
	Flow Rates, ml/min			Primary		Nitrification		Denitrification	
Time	Prim-N	Prim-D	Total	COD	TOC	COD	COD	COD	TOC
June 19-20, 1969									
8:30 am	3100	680	3780	341	96	44	20	118	30
10:00	4250	620	4870	--	91	--	20	102	32
12:00	5100	600	5700	338	95	52	21	118	31
2:00 pm	5600	650	6250	338	83	--	20	102	30
4:00	5500	760	6310	368	101	--	19	114	30
6:00	5250	920	6170	356	101	73	19	108	26
8:00	4650	1130	5780	315	90	73	17	106	26
10:00	3750	1280	5030	354	102	83	18	114	31
12:00	2900	1310	4210	412	110	67	18	94	36
2:00 am	2500	1240	3740	396	115	67	18	94	33
4:00	2400	1070	3470	408	120	52	17	78	31
6:00	2600	870	3470	368	110	69	17	98	33

Table 21

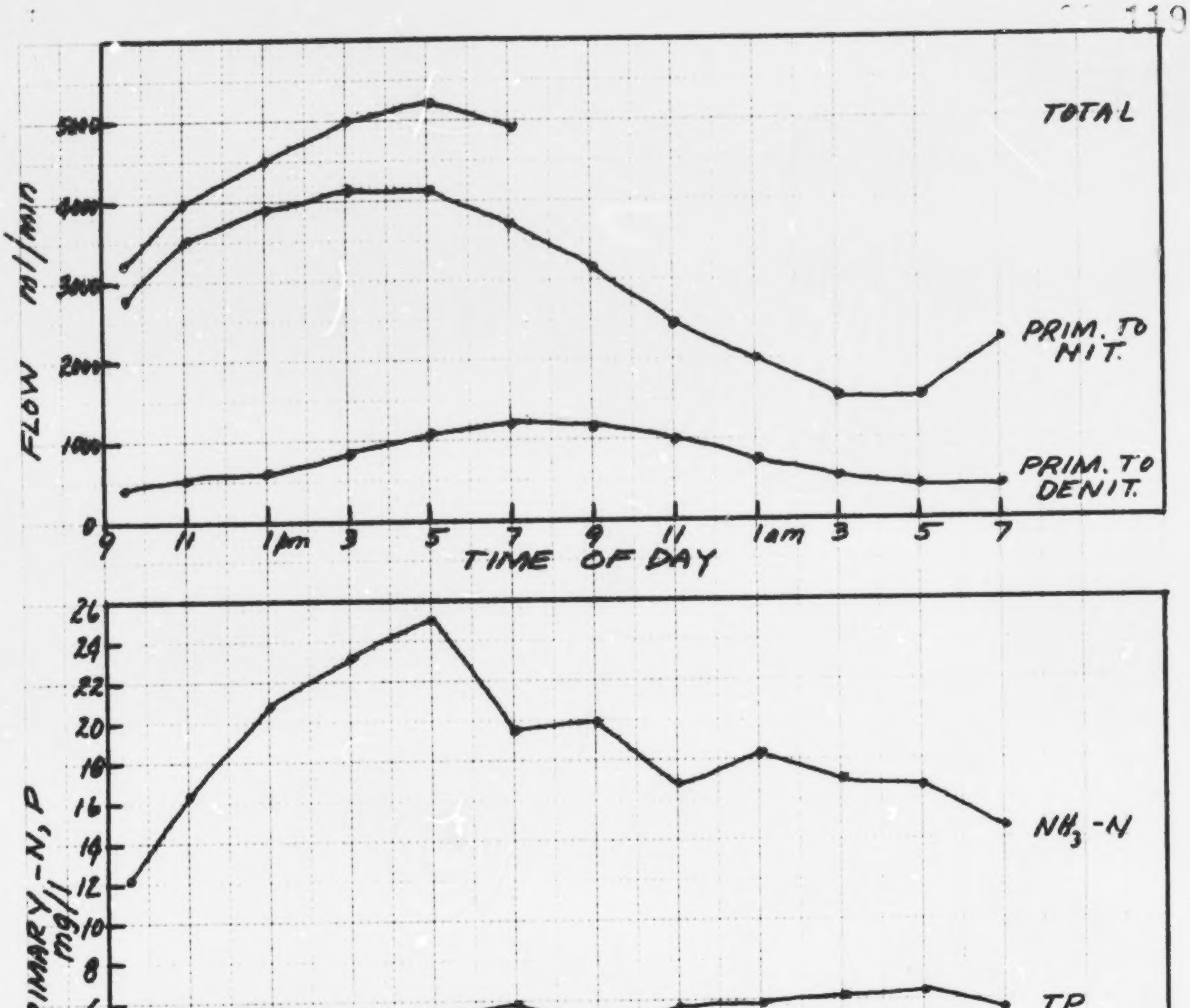
DEMONSTRATION PLANT HOURLY DATA

				Effluent Concentrations, mg/l								
	Flow Rates, ml/min			Primary			Nitrification			Denitrification		
Time	Prim-N	Prim-D	Total	NH_3-N	NO_3-N	TP	NH_3-N	NO_3-N	TP	NH_3-N	NO_3-N	TP
July 10-11, 1969												
7:30 am	2200	800	3000	6.8		10.5	0.9	8.4	4.0	3.5	--	--
9:30	2900	700	3600	5.8		5.7	0.8	8.8	4.1	2.6	0.4	2.8
11:30	3700	1000	4700	5.6		6.7	0.8	9.6	4.0	2.1	0.4	2.5
1:30 pm	4700	1200	5900	8.2		5.8	0.8	9.8	4.0	1.6	0.4	2.5
3:30	5300	1300	6600	7.4		7.3	0.9	8.2	3.7	1.5	0.4	2.2
5:30	5500	1200	6700	8.8		9.5	0.9	9.2	3.4	1.7	0.4	3.2
7:30	5000	1200	6200	8.0		10.0	0.8	8.8	3.3	1.7	0.4	3.5
9:30	4300	1100	5200	7.9		8.4	0.9	8.8	3.5	2.2	0.4	3.4
11:30	3300	800	4100	9.2		8.5	0.9	9.0	3.4	2.8	0.4	4.2
1:30 am	2500	800	3300	8.0		7.9	0.9	9.6	3.7	2.4	0.4	3.6
3:30	2000	800	2800	5.2		6.7	1.0	9.6	3.4	2.8	0.4	4.1
5:30	1900	800	2700	5.8		7.3	0.9	11.4	4.5	3.0	0.4	4.2



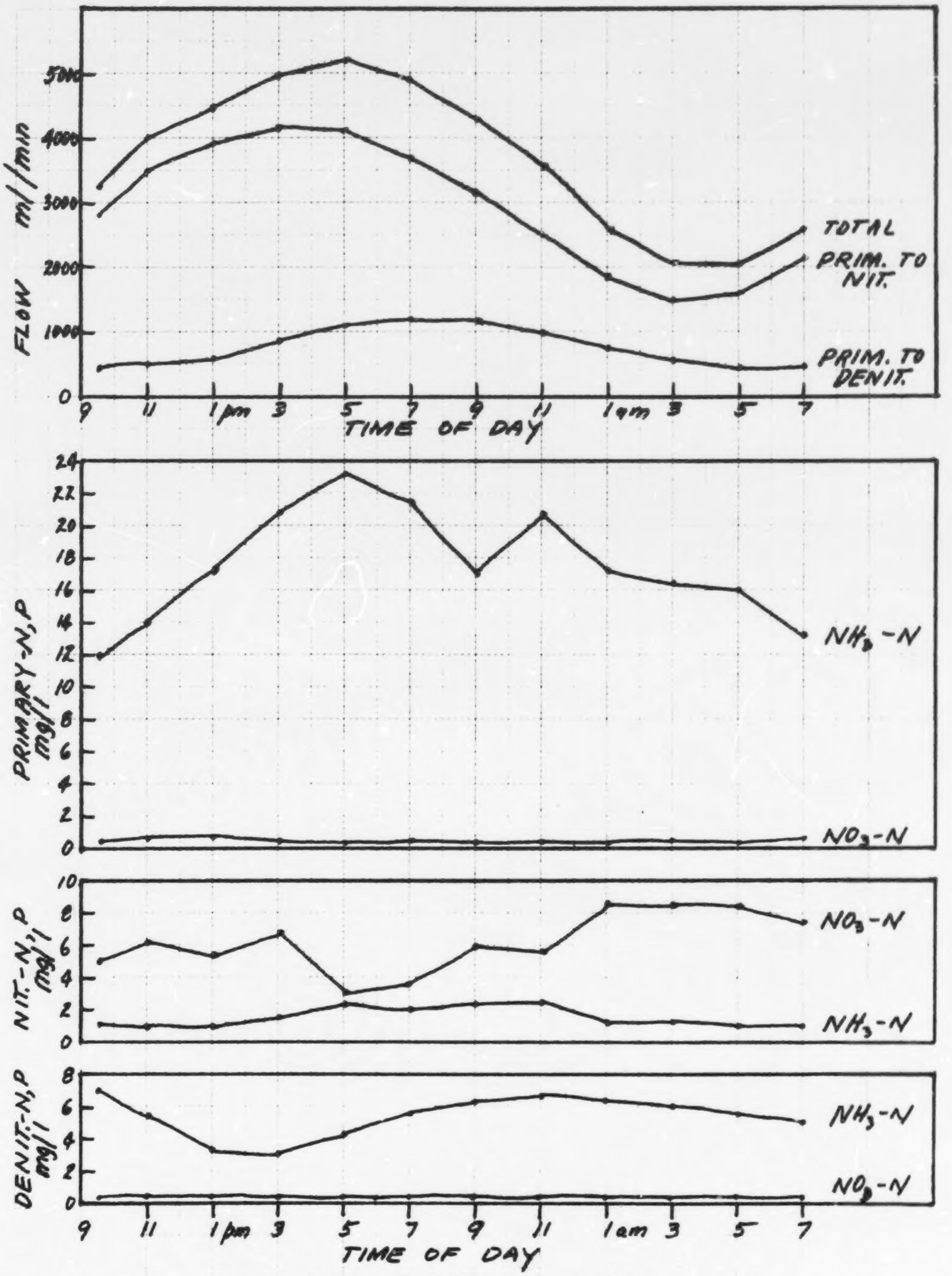
24-HOUR SAMPLING DATA
JANUARY 6-7, 1969

FIGURE 19



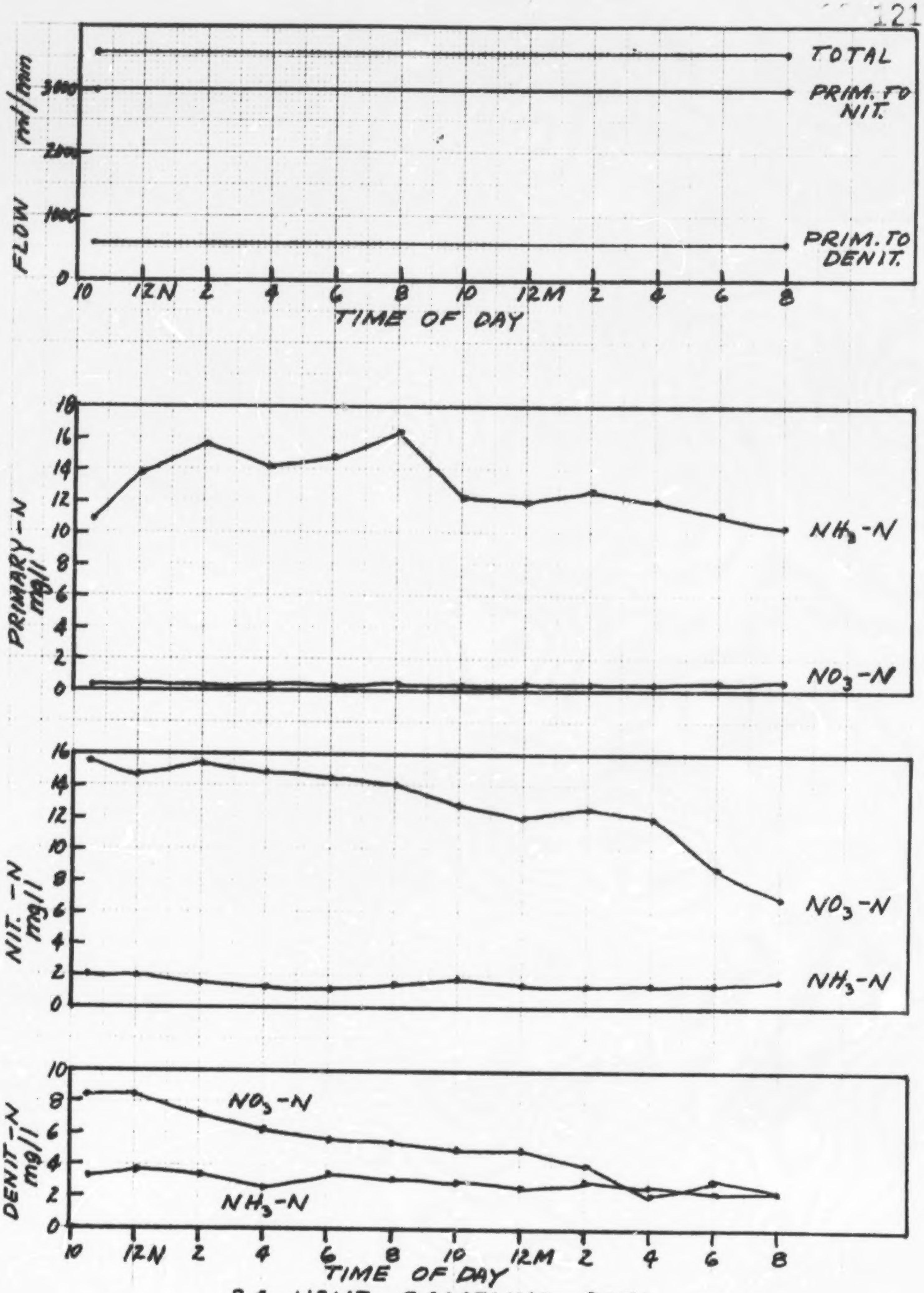
24-HOUR SAMPLING DATA
JANUARY 7-8, 1969

FIGURE 20



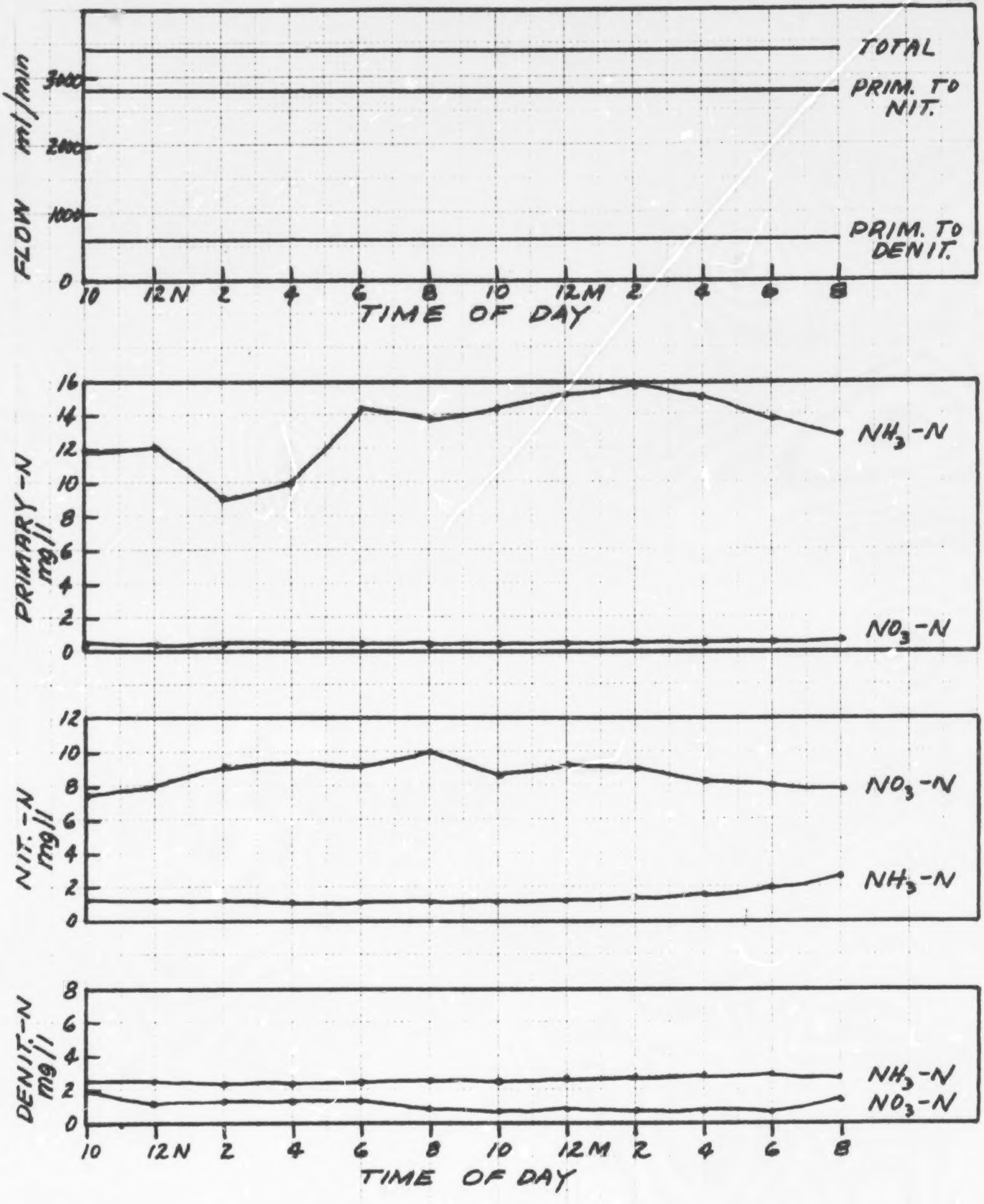
24-HOUR SAMPLING DATA
JANUARY 8-9, 1969

FIGURE 21



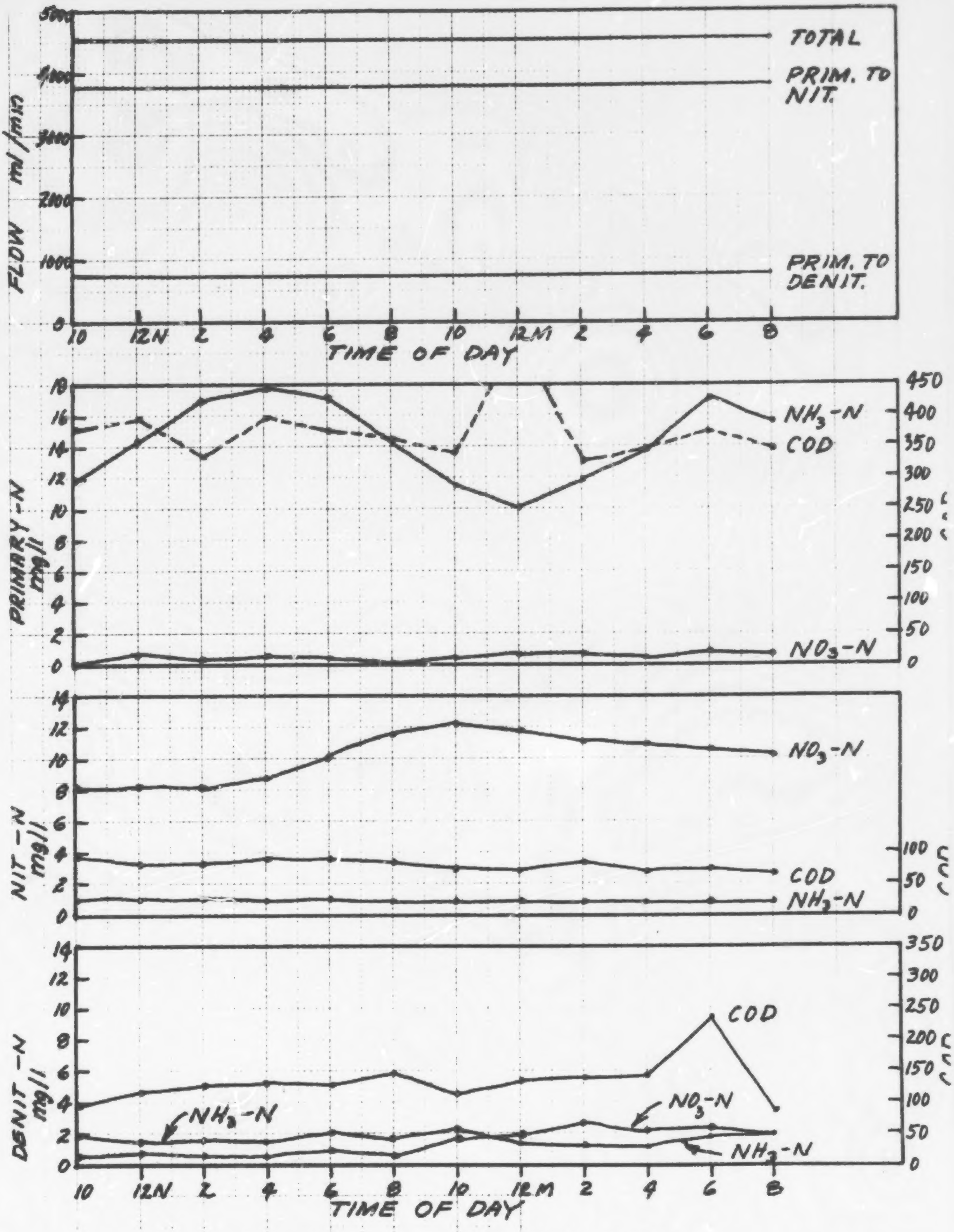
24-HOUR SAMPLING DATA
APRIL 7-8. 1969

FIGURE 22



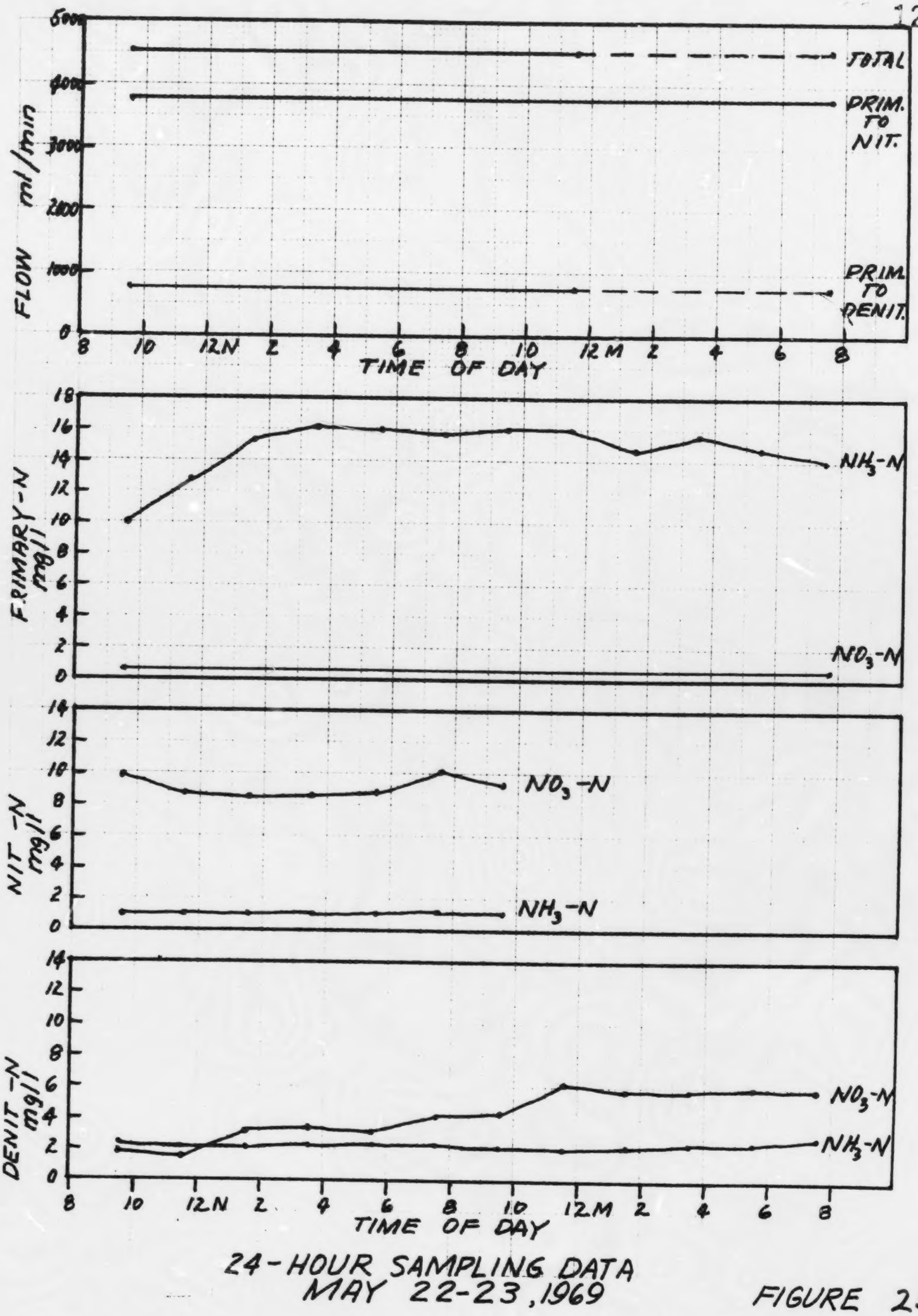
24-HOUR SAMPLING DATA
APRIL 8-9, 1969

FIGURE 23



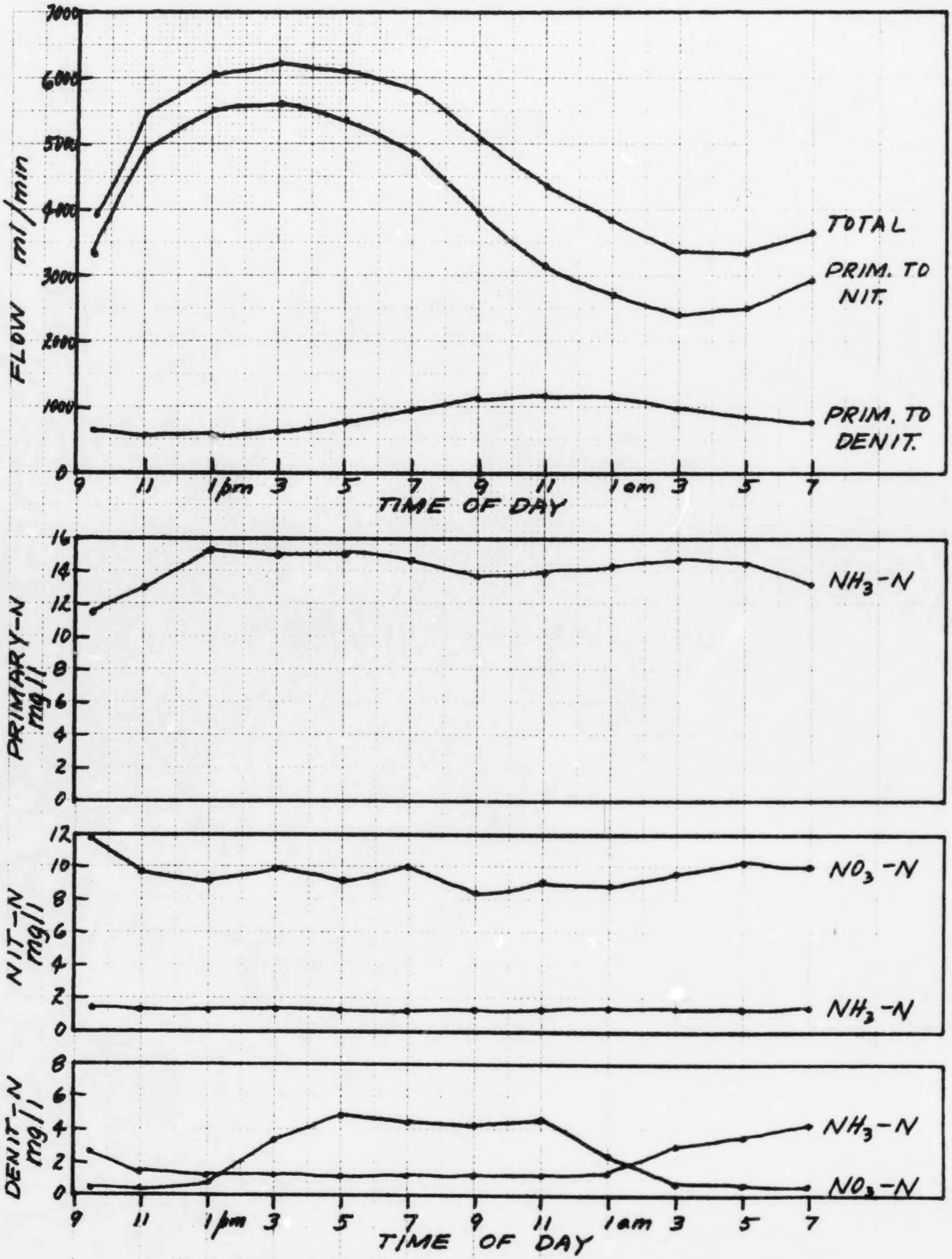
24-HOUR SAMPLING DATA
MAY 21-22, 1969

FIGURE 24



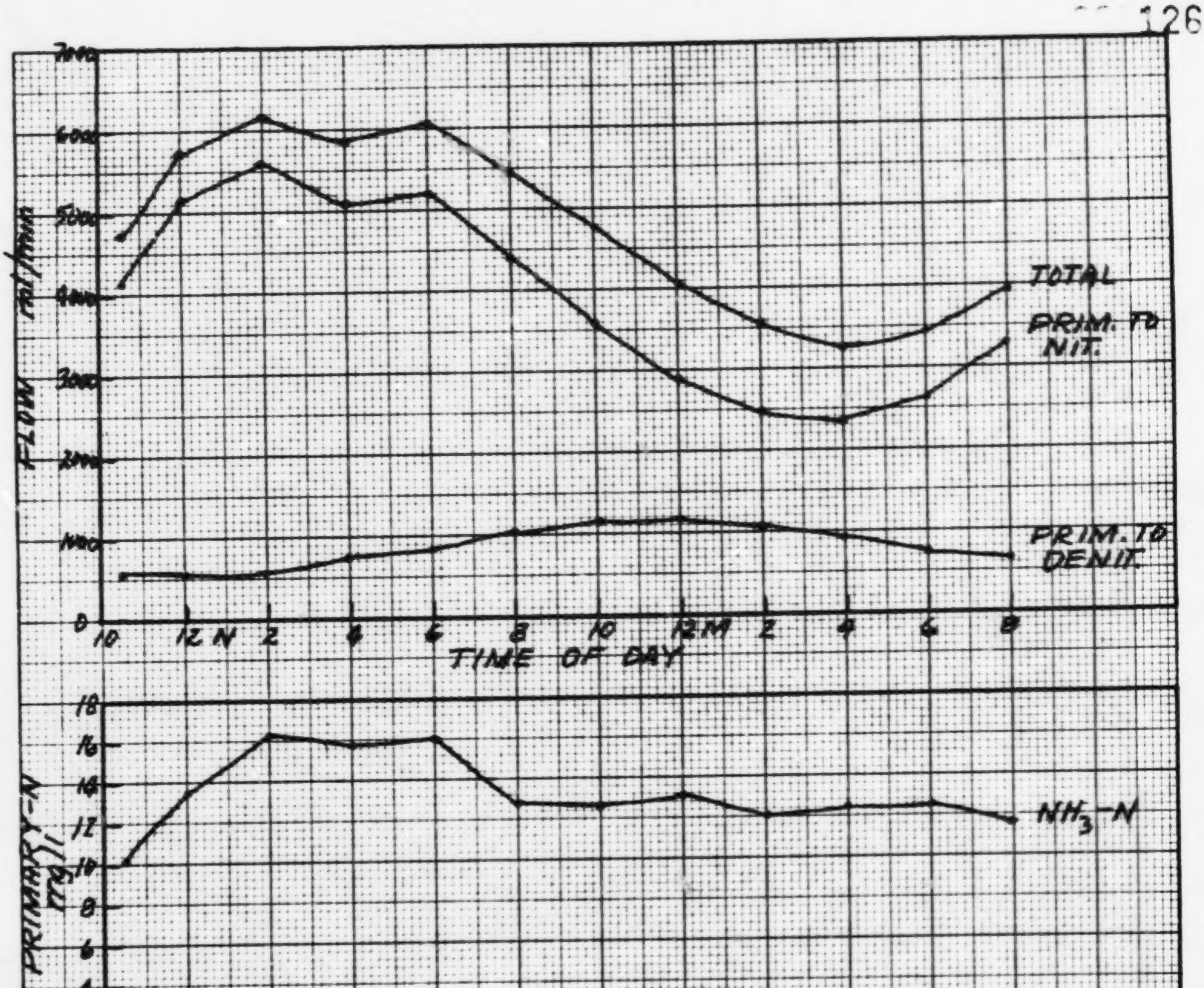
24-HOUR SAMPLING DATA
MAY 22-23, 1969

FIGURE 25



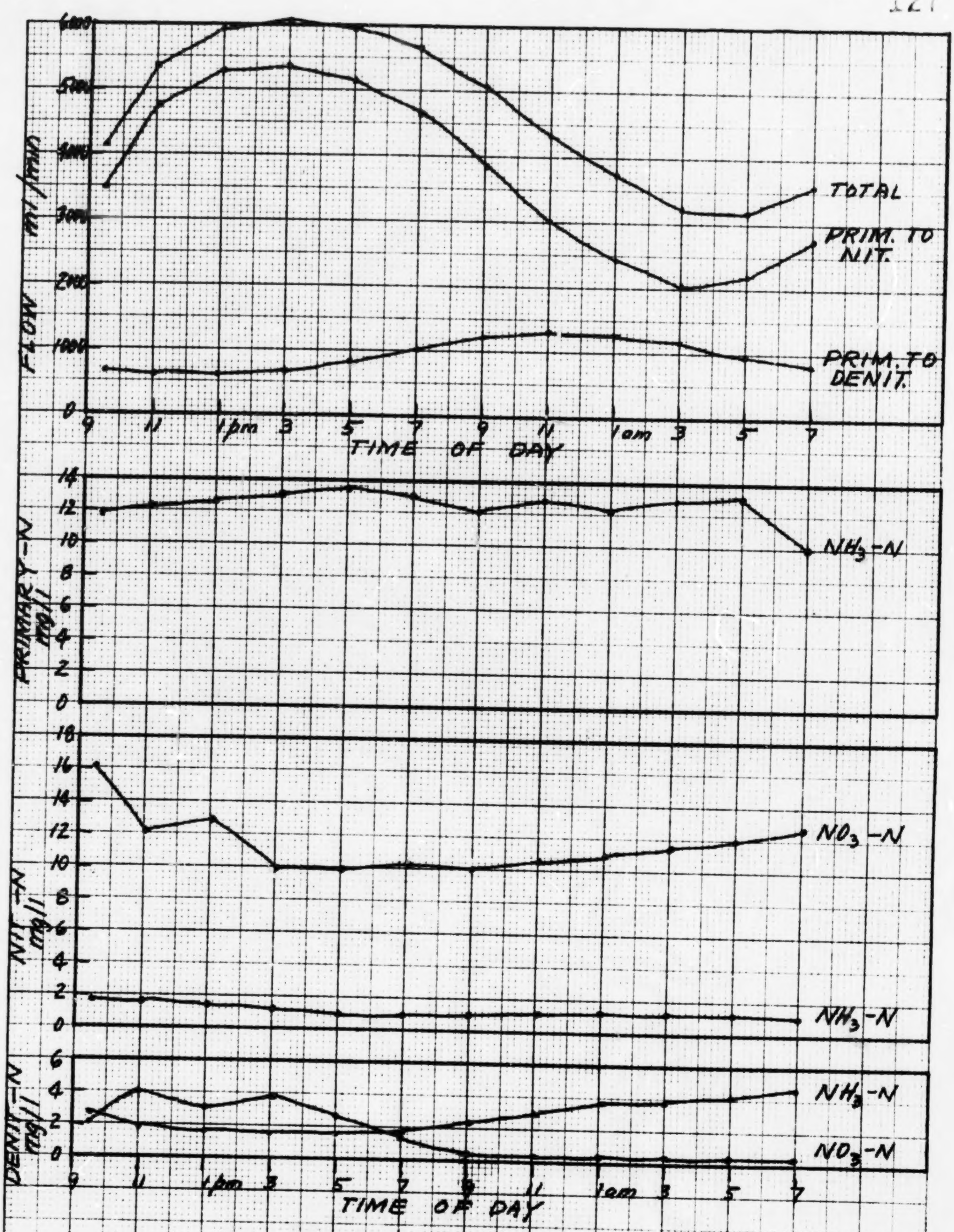
24-HOUR SAMPLING DATA
JUNE 4-5, 1969

FIGURE 26



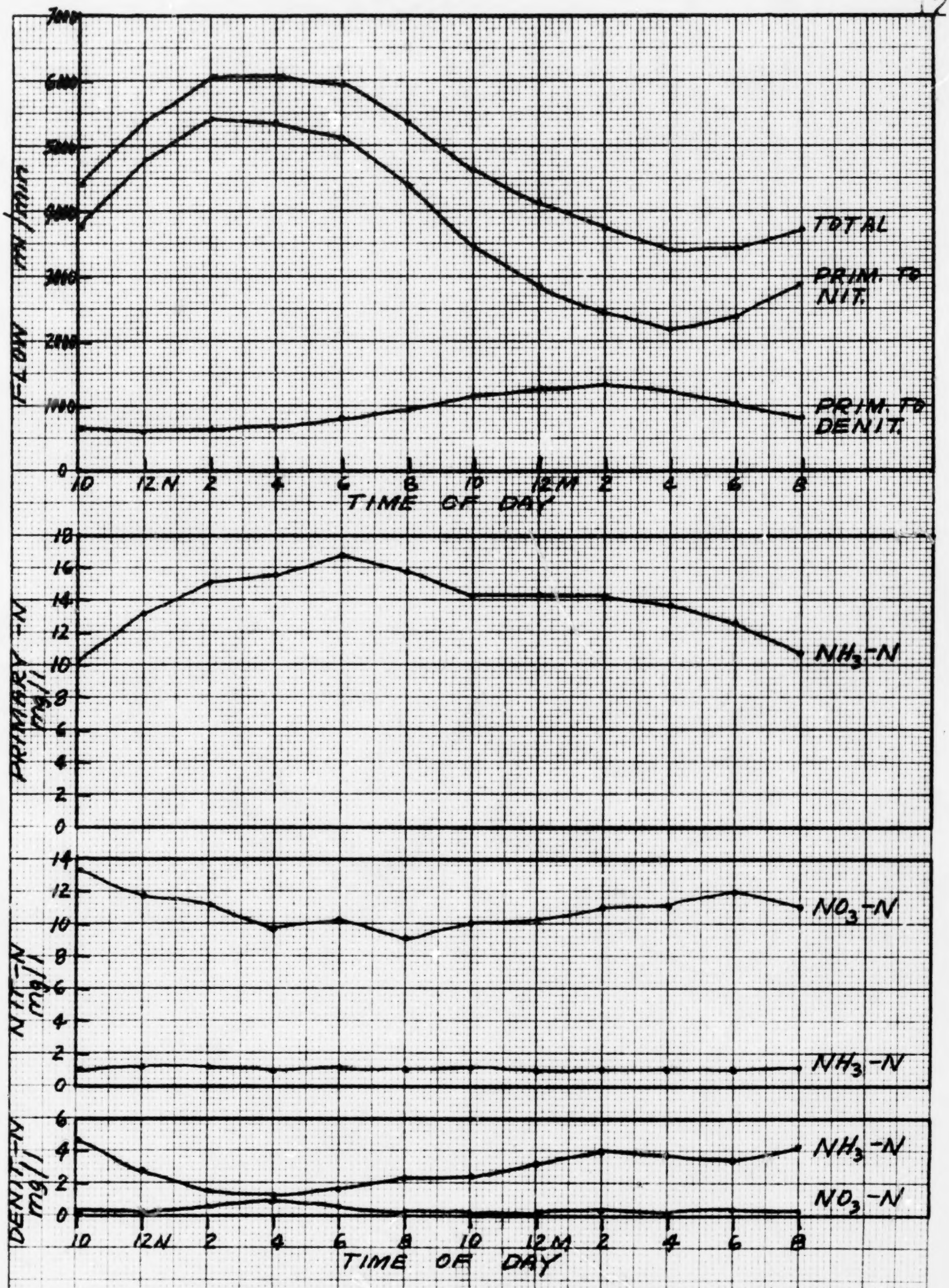
24-HOUR SAMPLING DATA
JUNE 5-6, 1969

FIGURE 27



24-HOUR SAMPLING DATA
JUNE 16-17, 1969

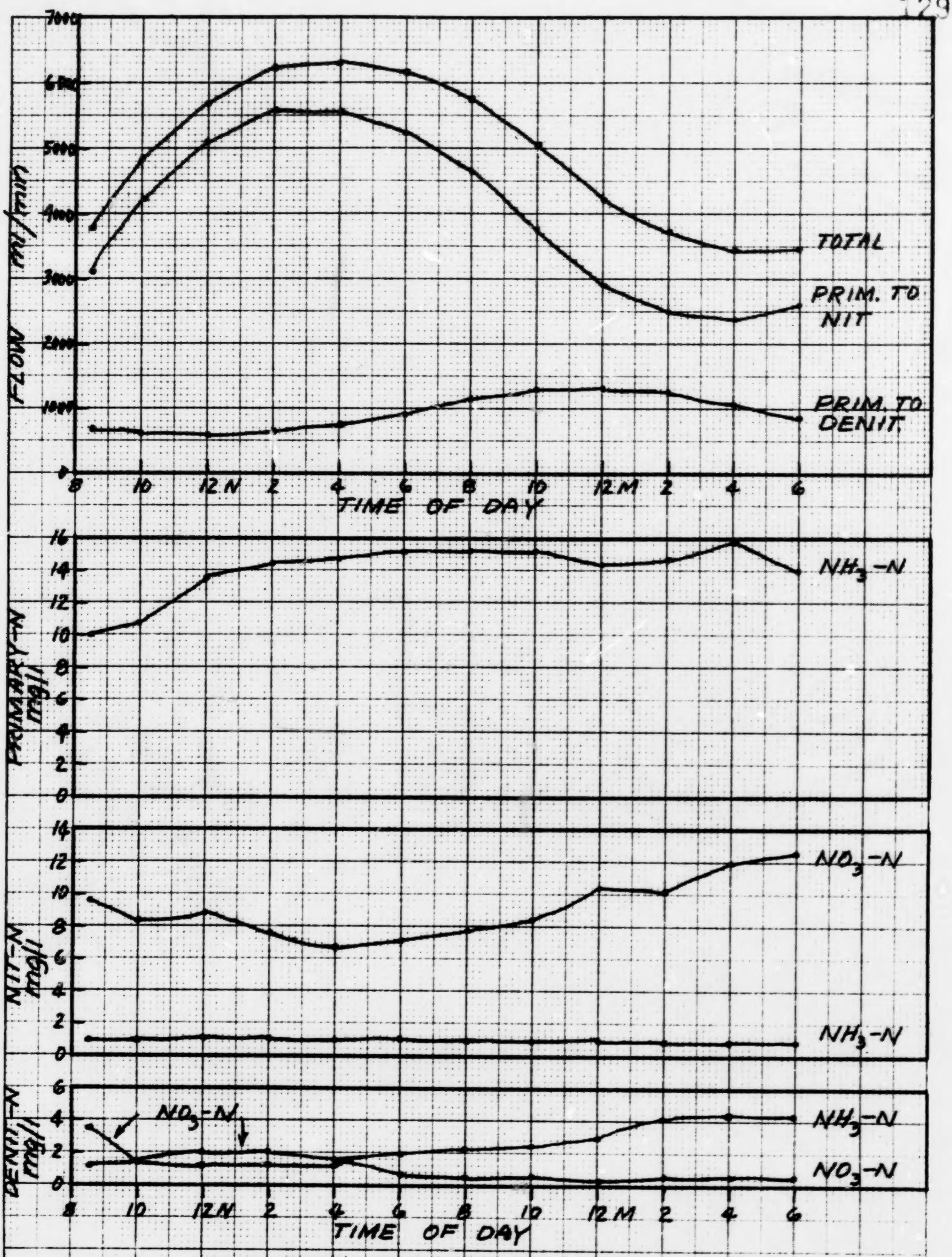
FIGURE 28



24-HOUR SAMPLING DATA

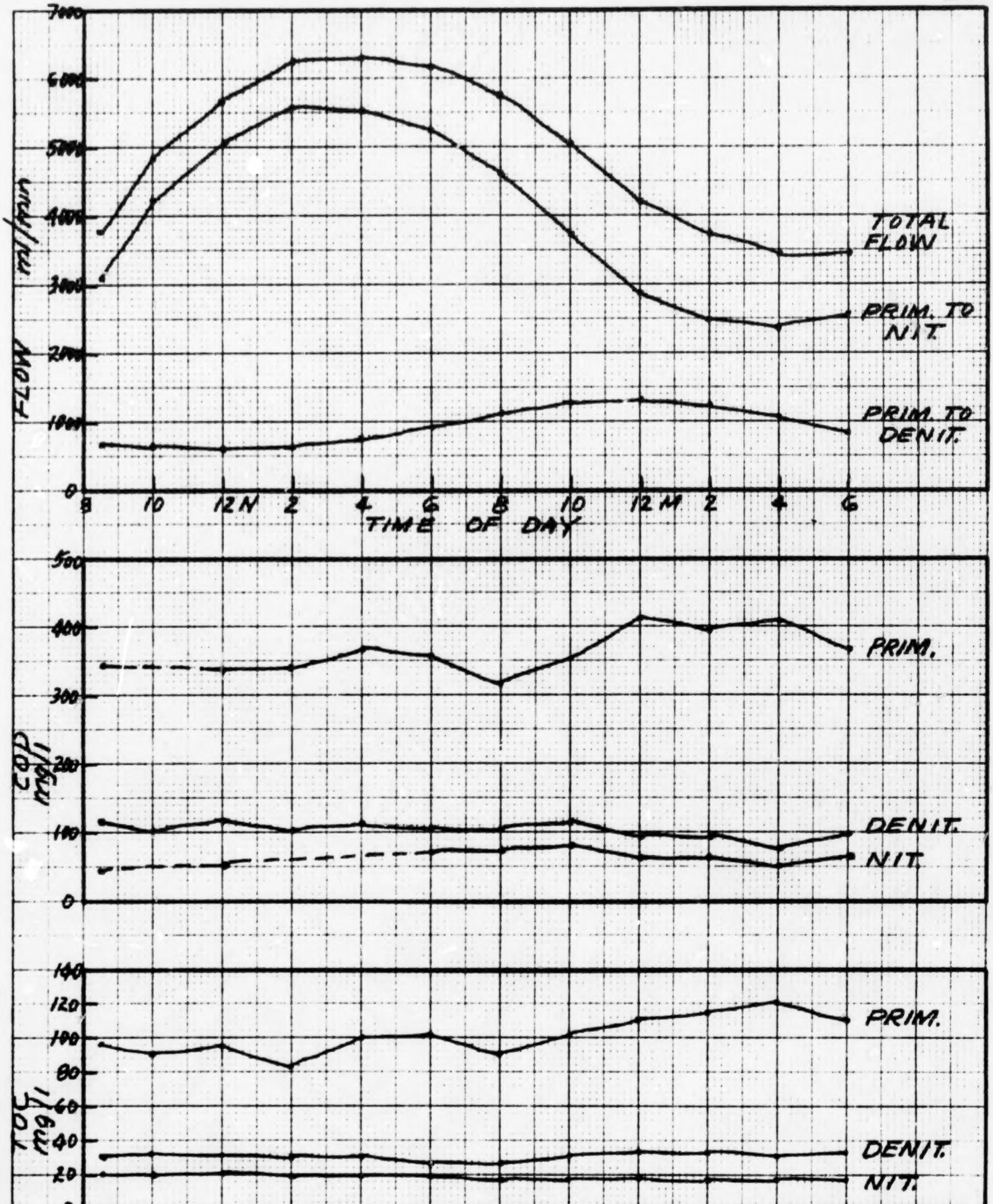
JUNE 17-18, 1969

FIGURE 29



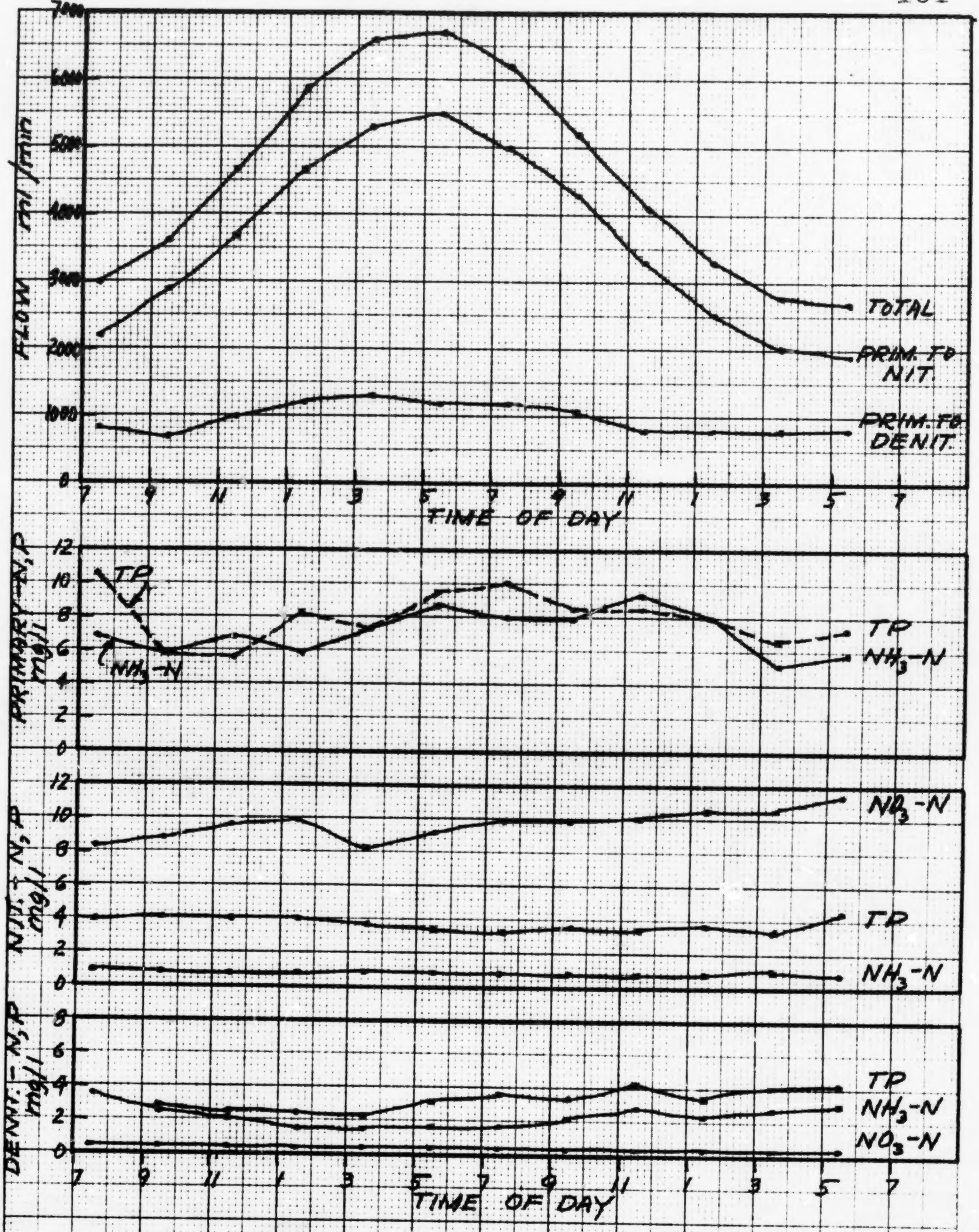
24-HOUR SAMPLING DATA
JUNE 19-20, 1969

FIGURE 30



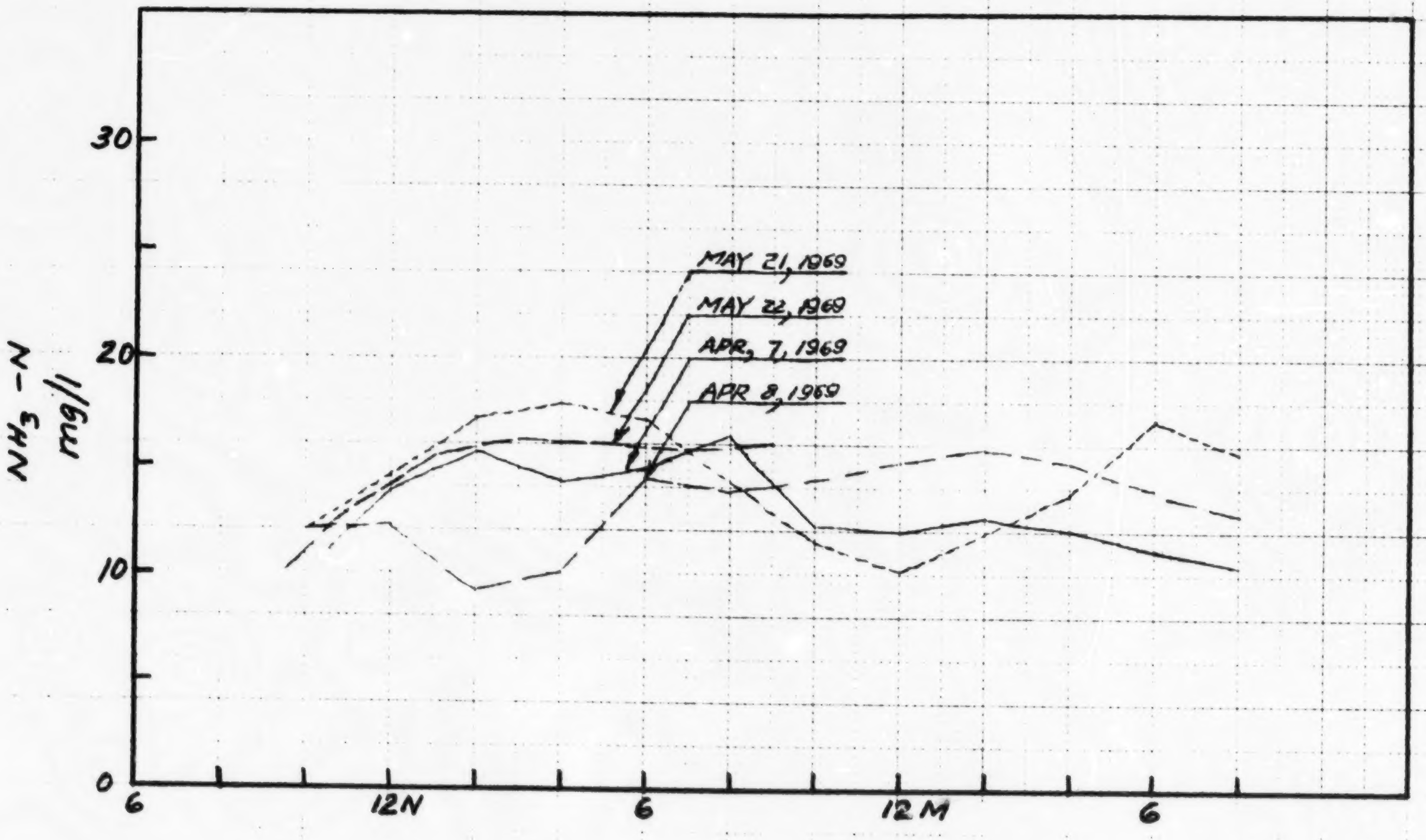
24-HOUR SAMPLING DATA
JUNE 19-20, 1969

FIGURE 31



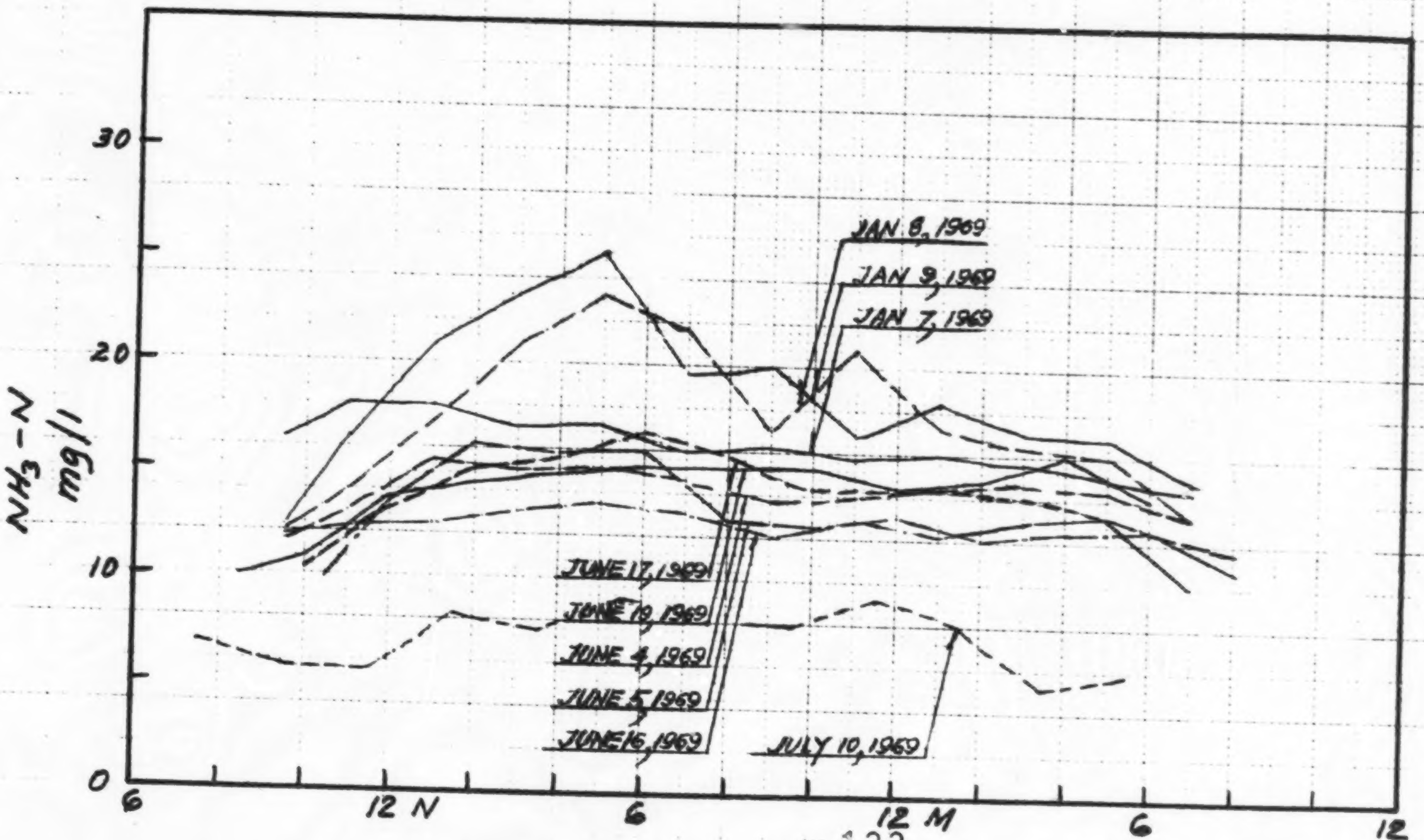
24-HOUR SAMPLING DATA
JULY 10-11, 1969

FIGURE 32



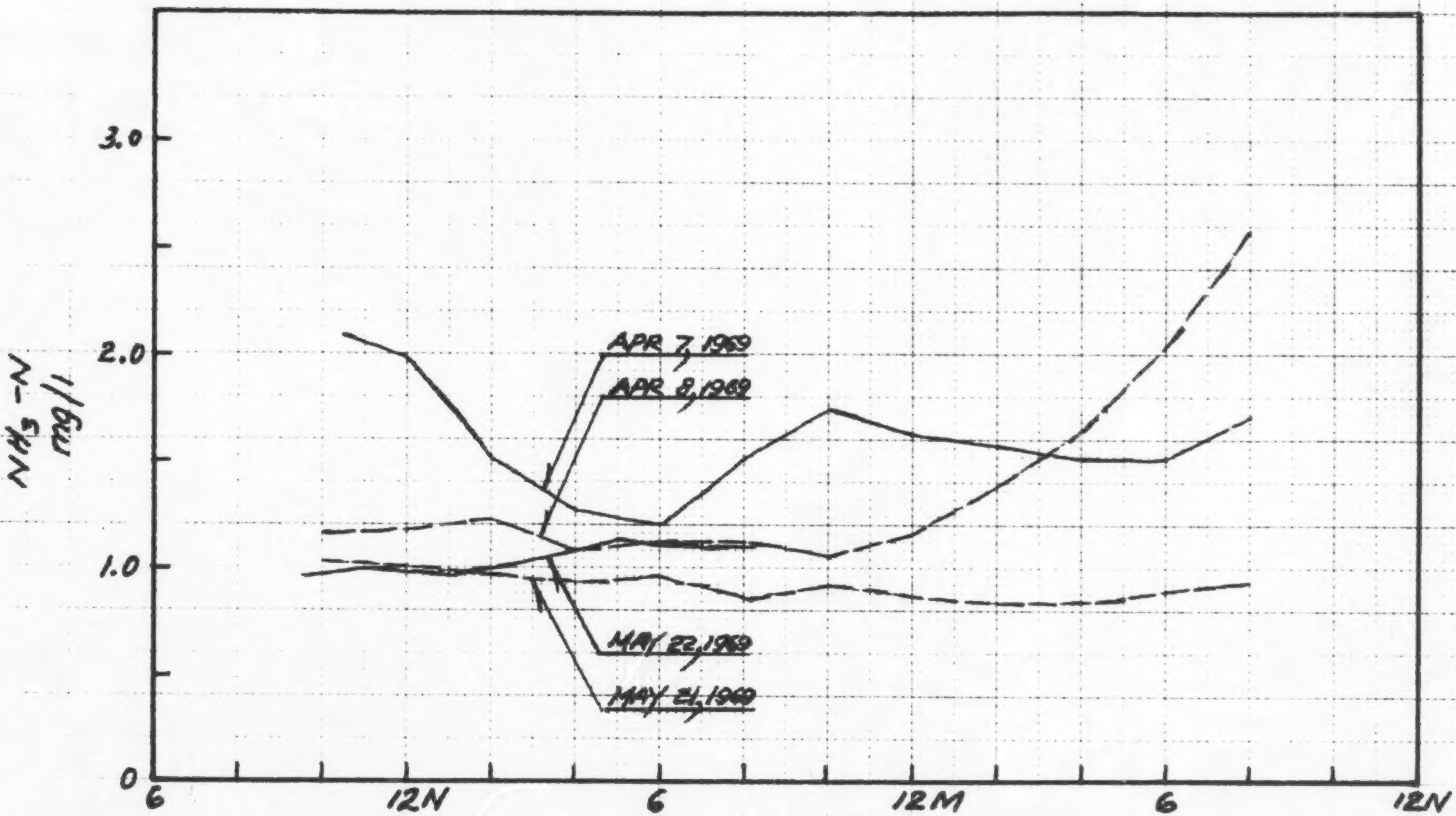
24-HOUR SAMPLING DATA SUMMARY
PRIMARY NH_3-N , CONSTANT FLOW

FIGURE 33



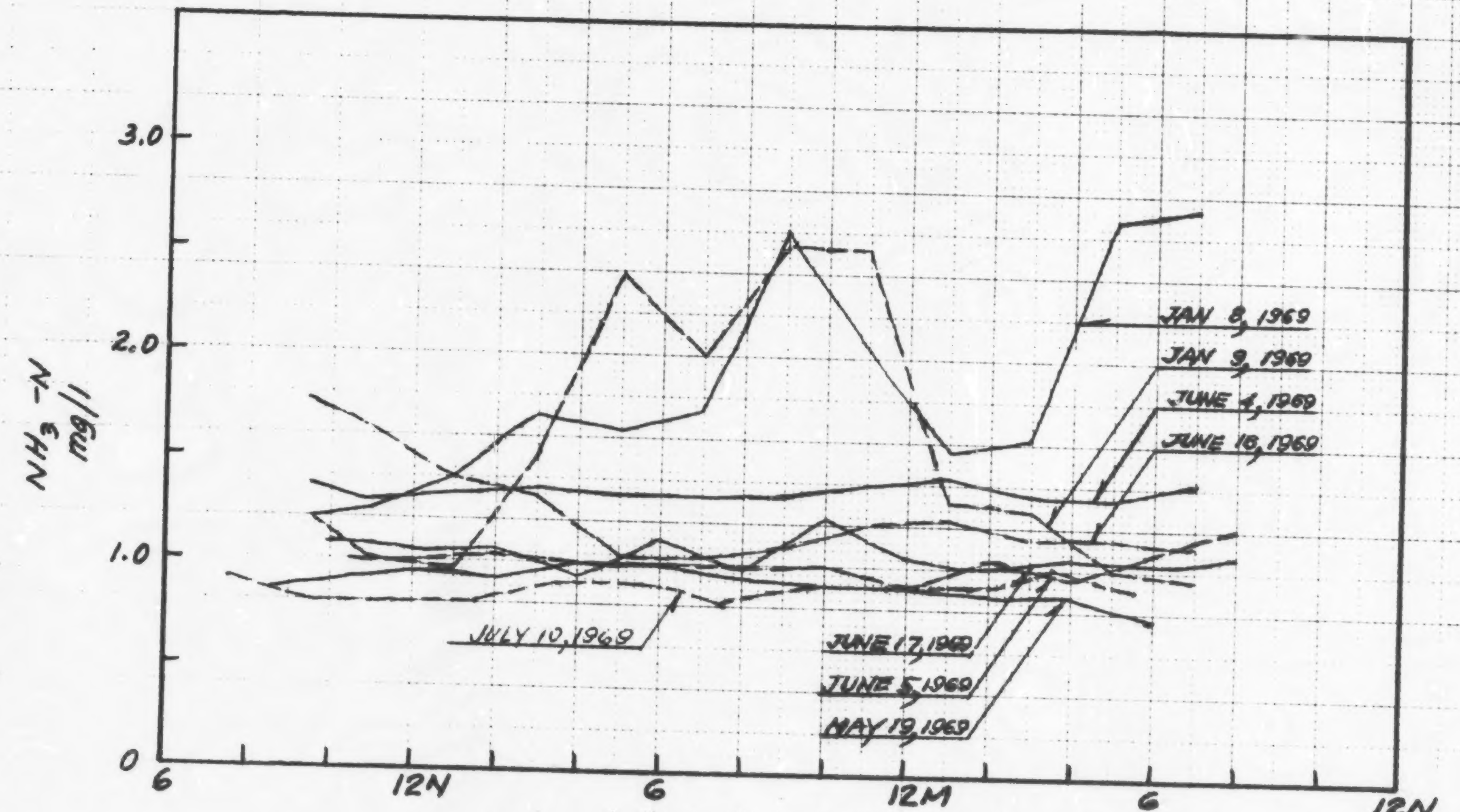
24-HOUR SAMPLING DATA SUMMARY
PRIMARY NH$_3$-N, VARIABLE FLOW

FIGURE 34



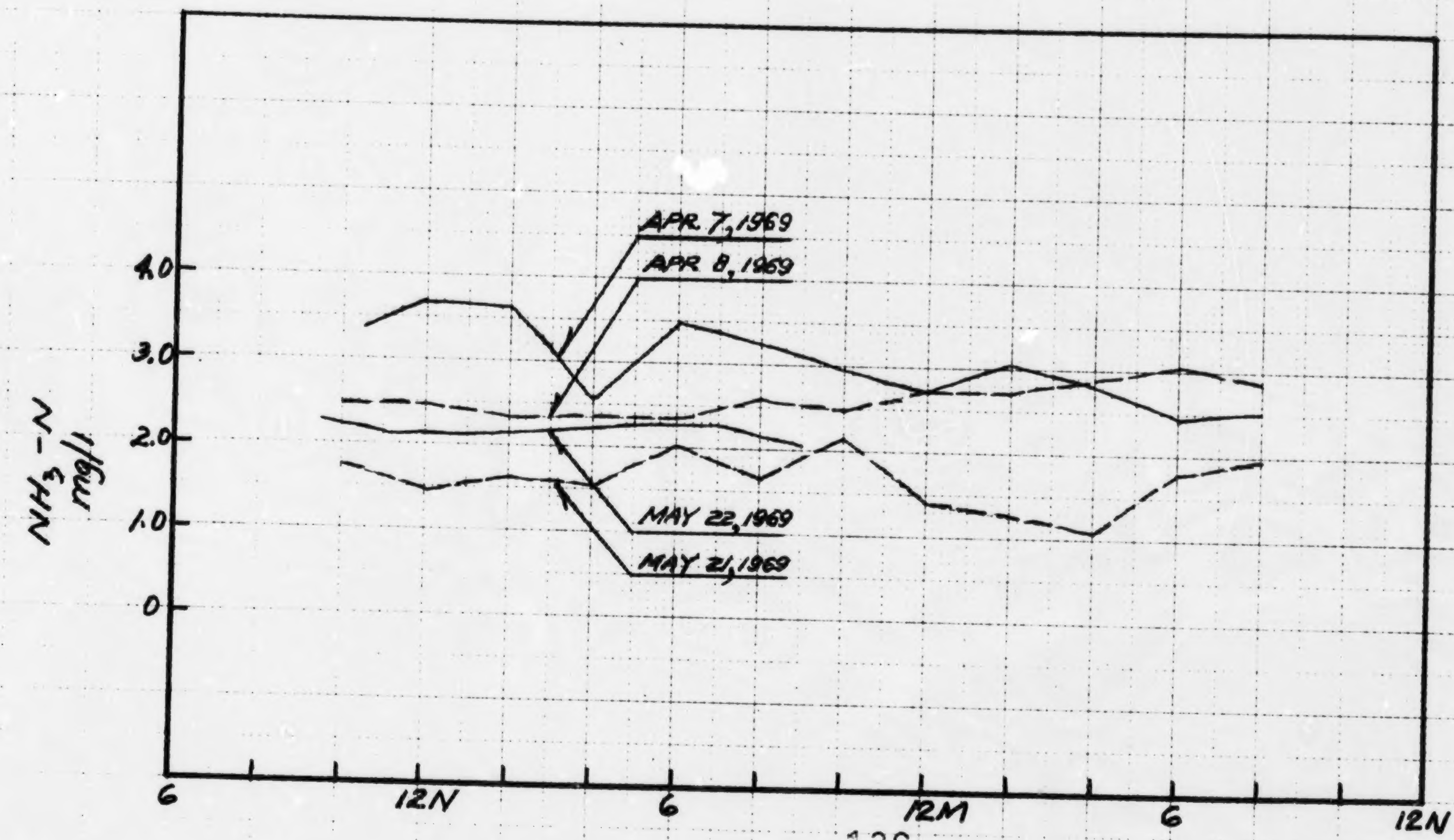
24-HOUR SAMPLING DATA SUMMARY
NITRIFICATION NH_3-N, CONSTANT FLOW

FIGURE 35



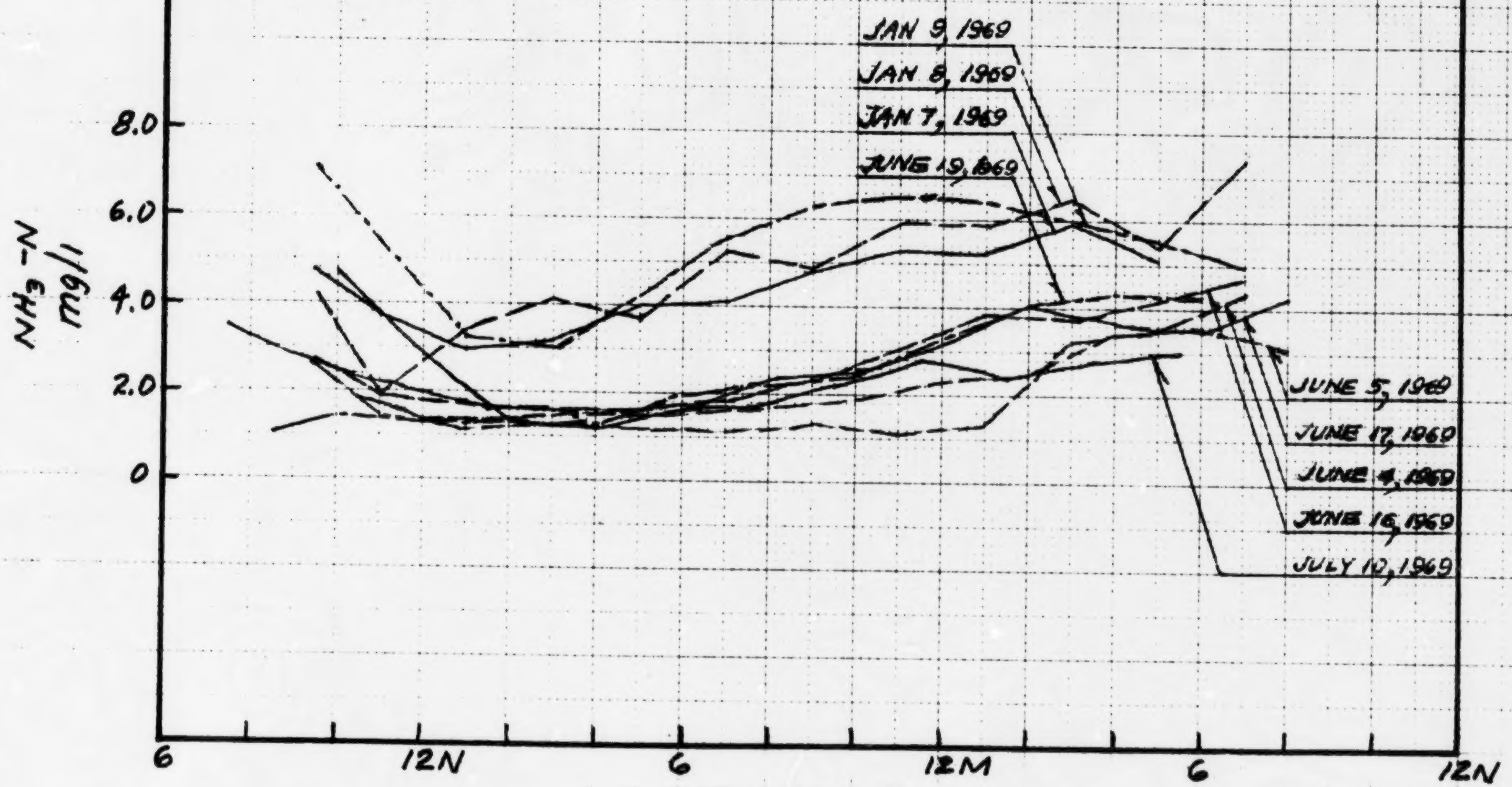
24-HOUR SAMPLING DATA SUMMARY
NITRIFICATION NH_3-N, VARIABLE FLOW

FIGURE 36



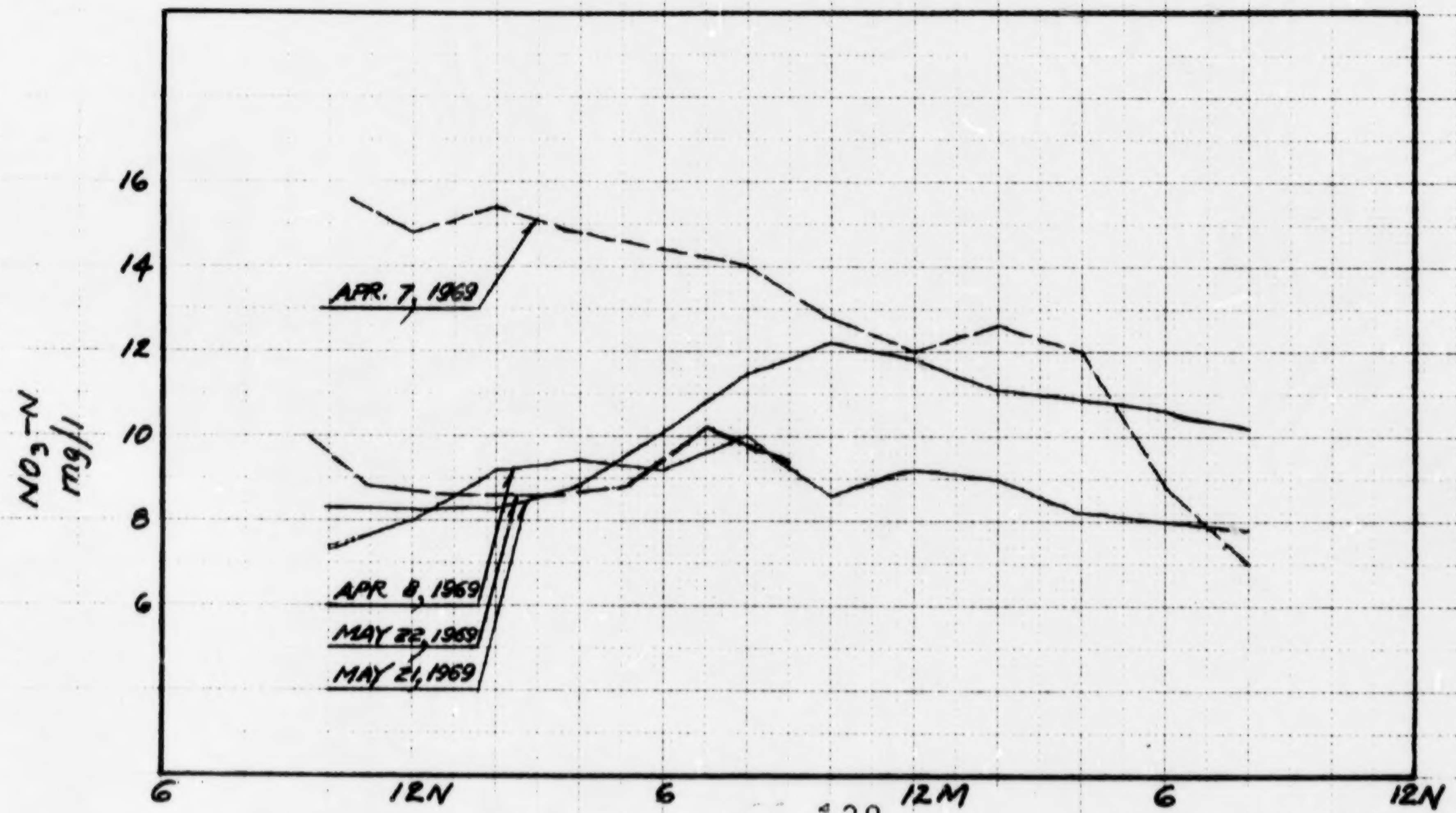
24-HOUR SAMPLING DATA SUMMARY
DENITRIFICATION NH$_3$-N, CONSTANT FLOW

FIGURE 37



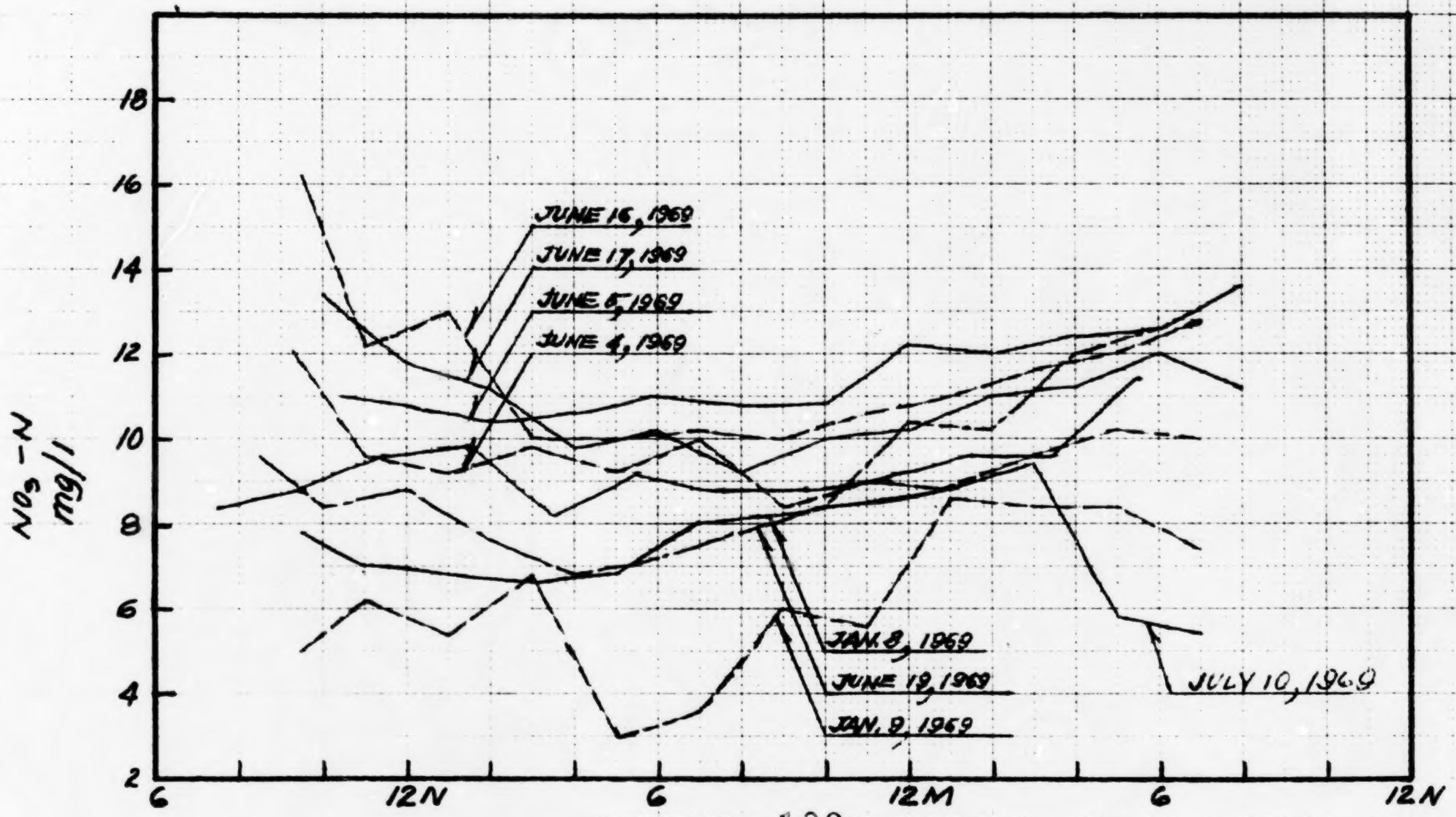
24-HOUR SAMPLING DATA SUMMARY
DENITRIFICATION NH_3-N, VARIABLE FLOW

FIGURE 38



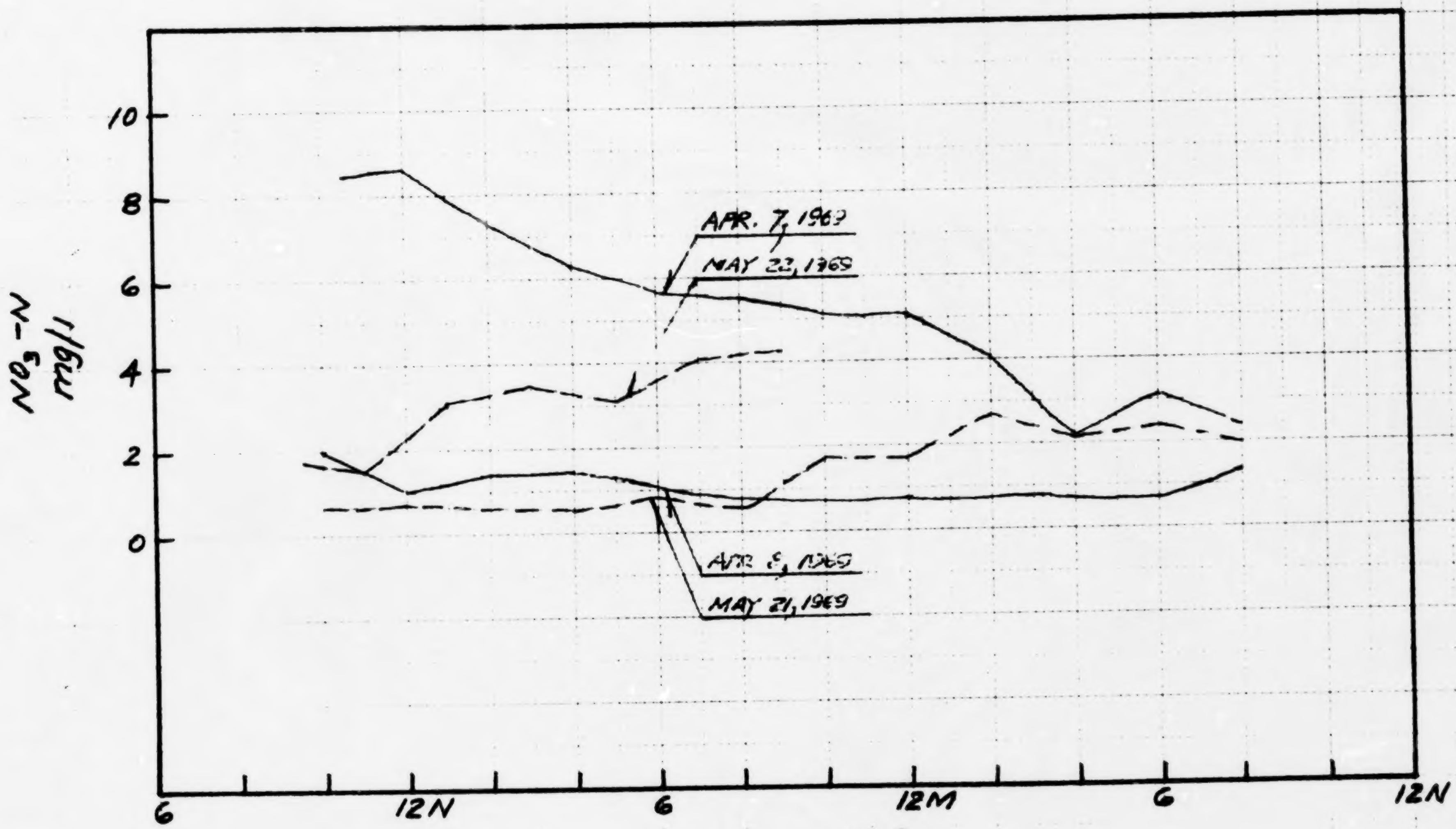
24-HOUR SAMPLING DATA SUMMARY
NITRIFICATION NO_3-N , CONSTANT FLOW

FIGURE 39



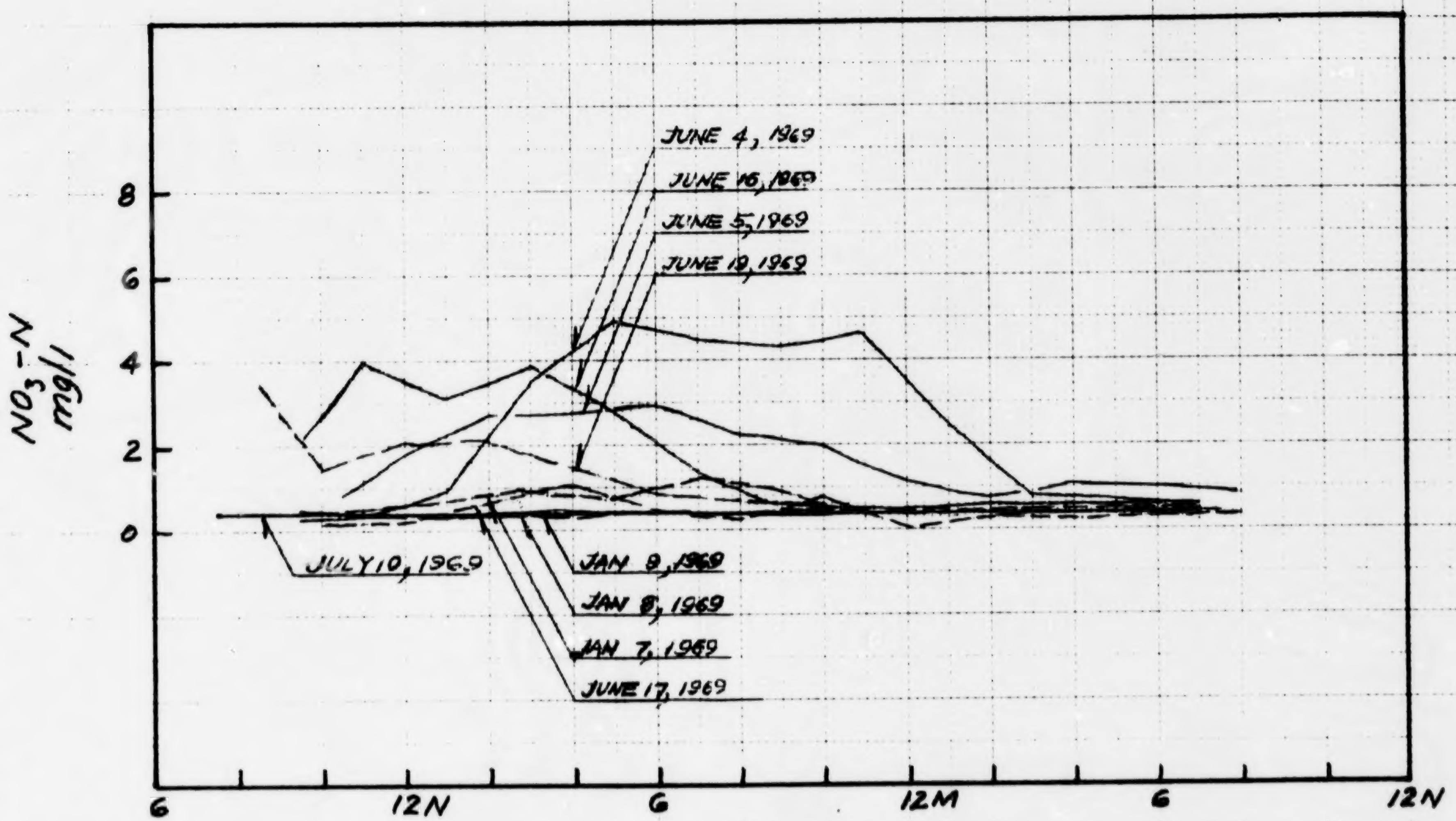
24-HOUR SAMPLING DATA SUMMARY
NITRIFICATION NO_3-N, VARIABLE FLOW

FIGURE 40



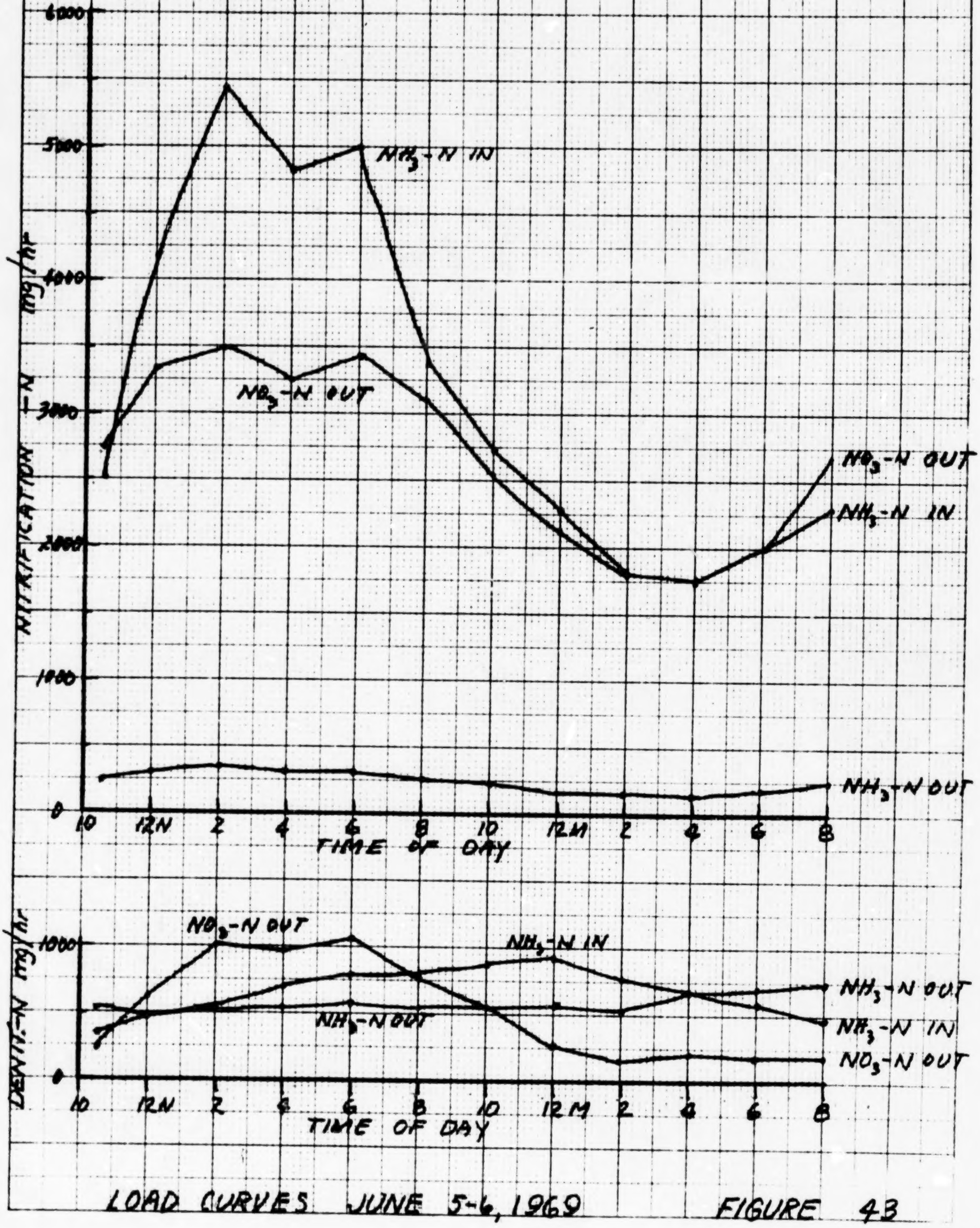
24-HOUR SAMPLING DATA SUMMARY
DENITRIFICATION NO_3-N, CONSTANT FLOW

FIGURE 41

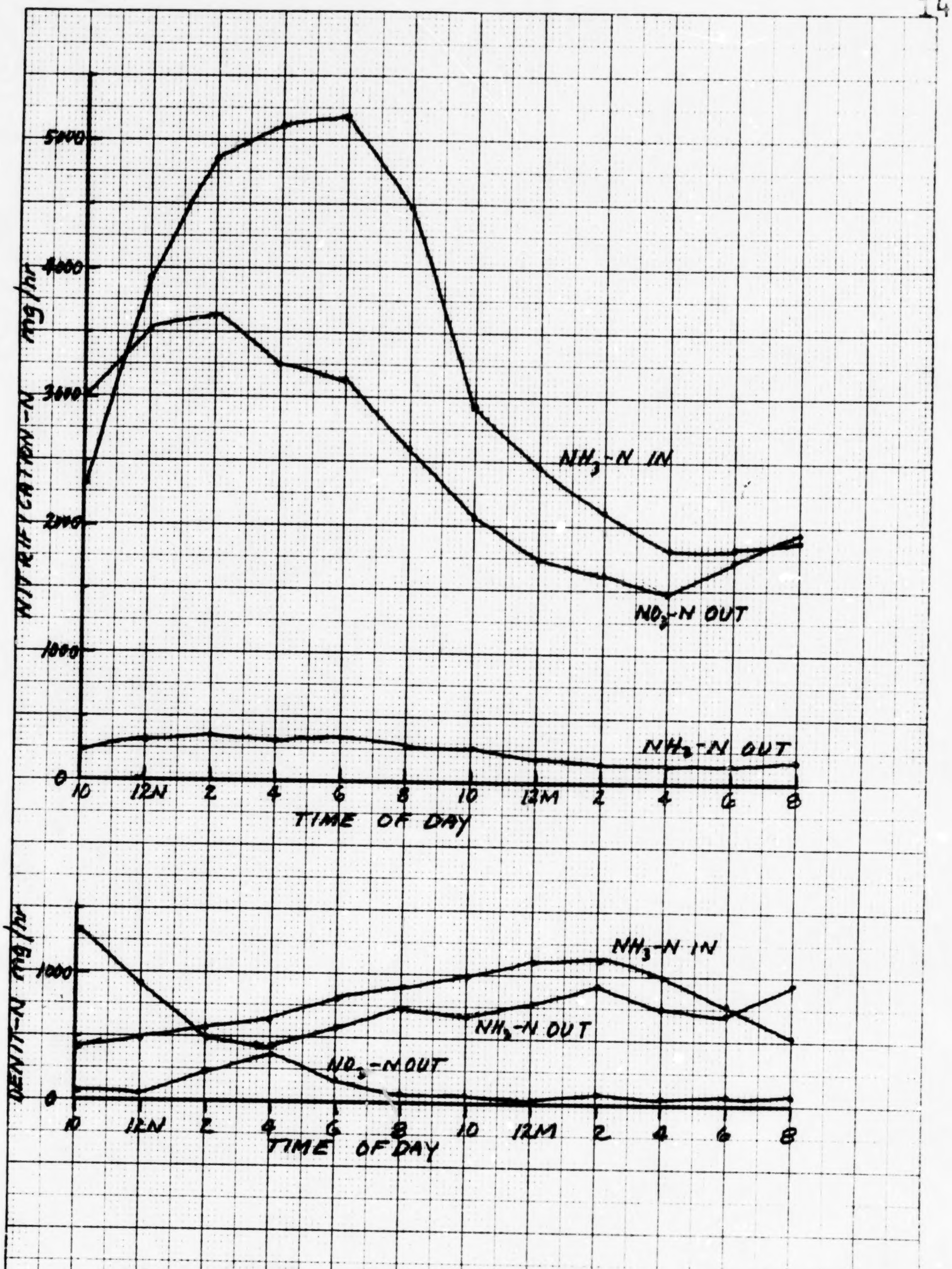


24-HOUR SAMPLING DATA SUMMARY
DENITRIFICATION NO_3-N, VARIABLE FLOW

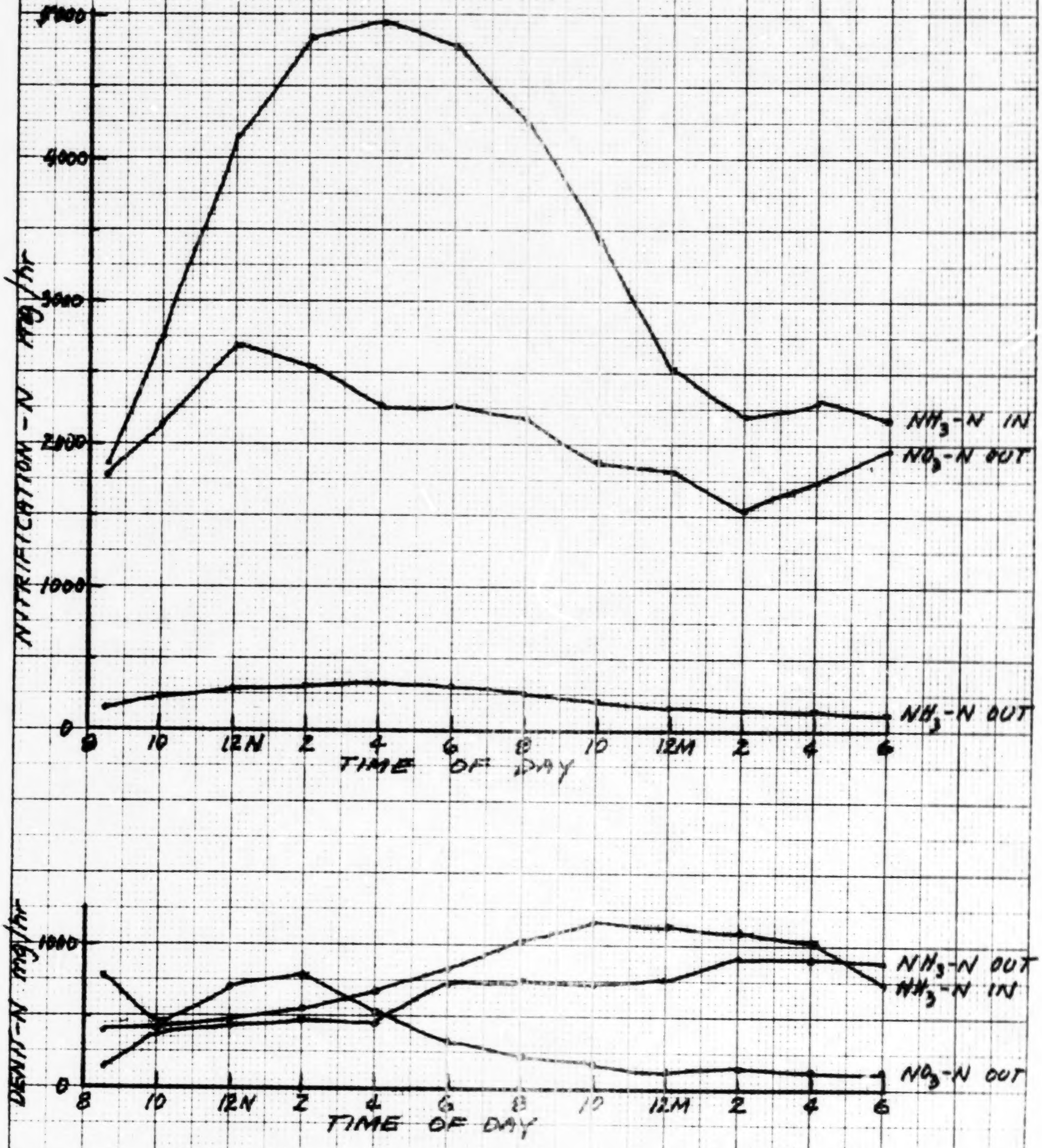
FIGURE 42



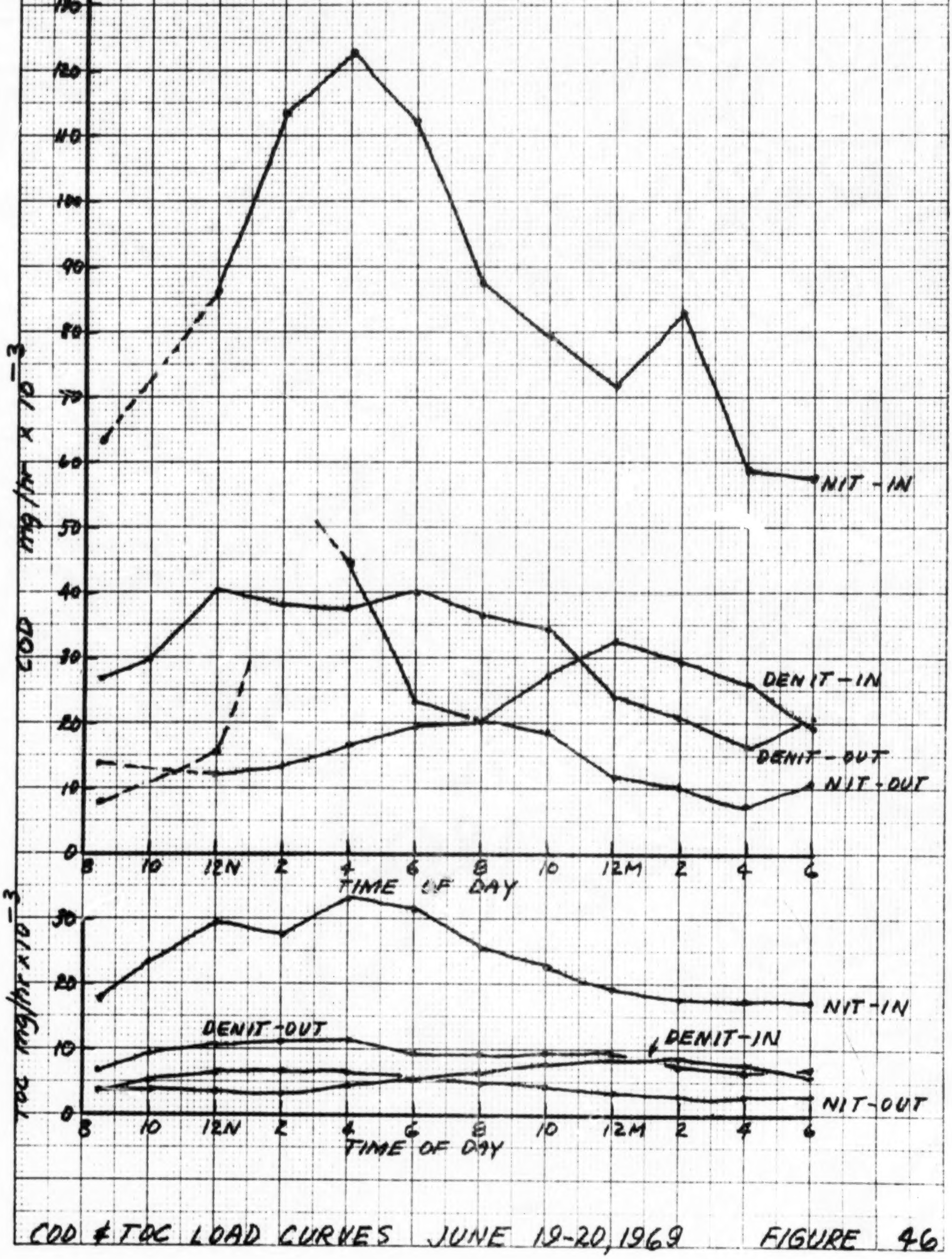
LOAD CURVES JUNE 5-6, 1969 FIGURE 43



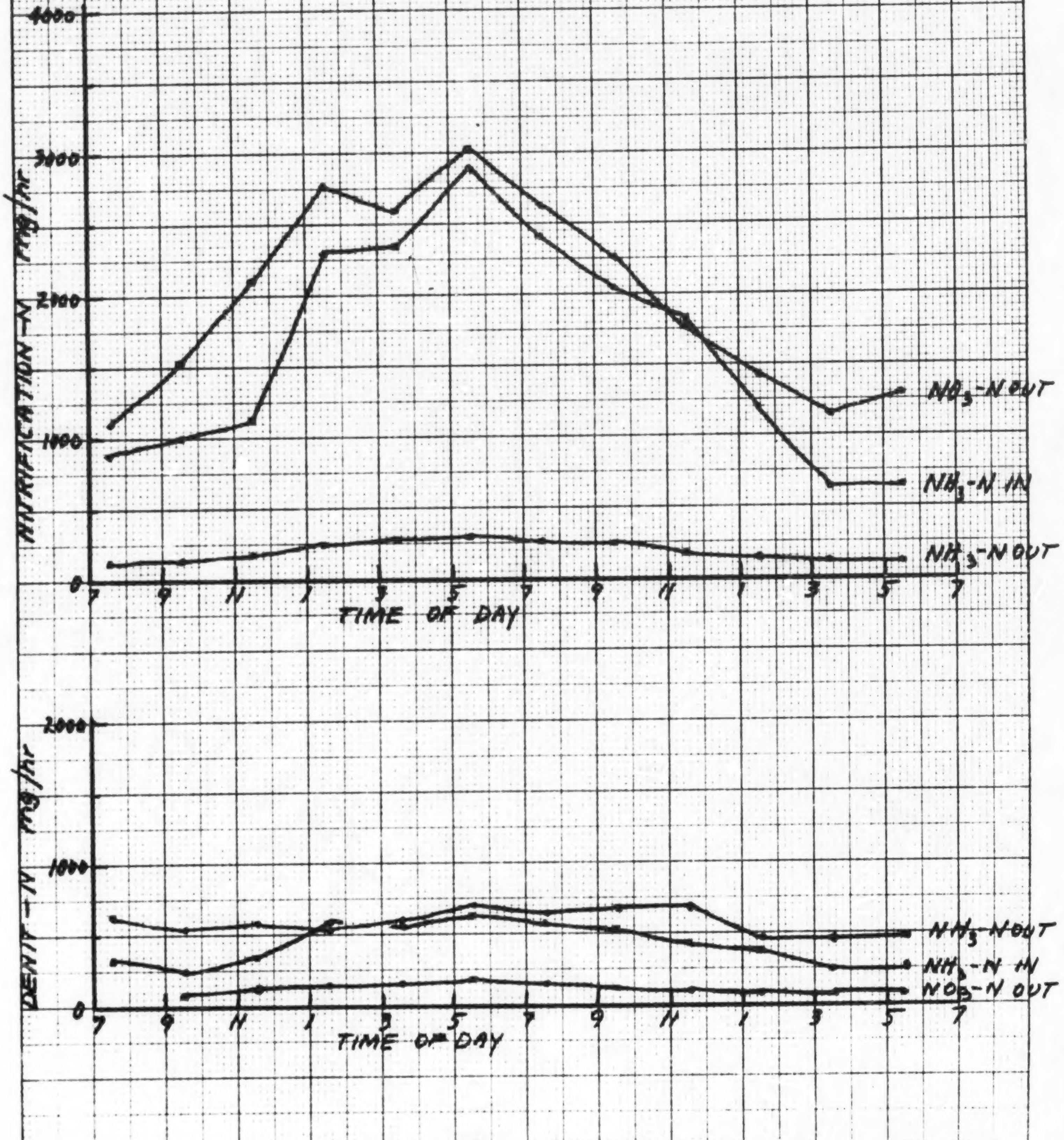
LOAD CURVES JUNE 17-18, 1969 FIGURE 44



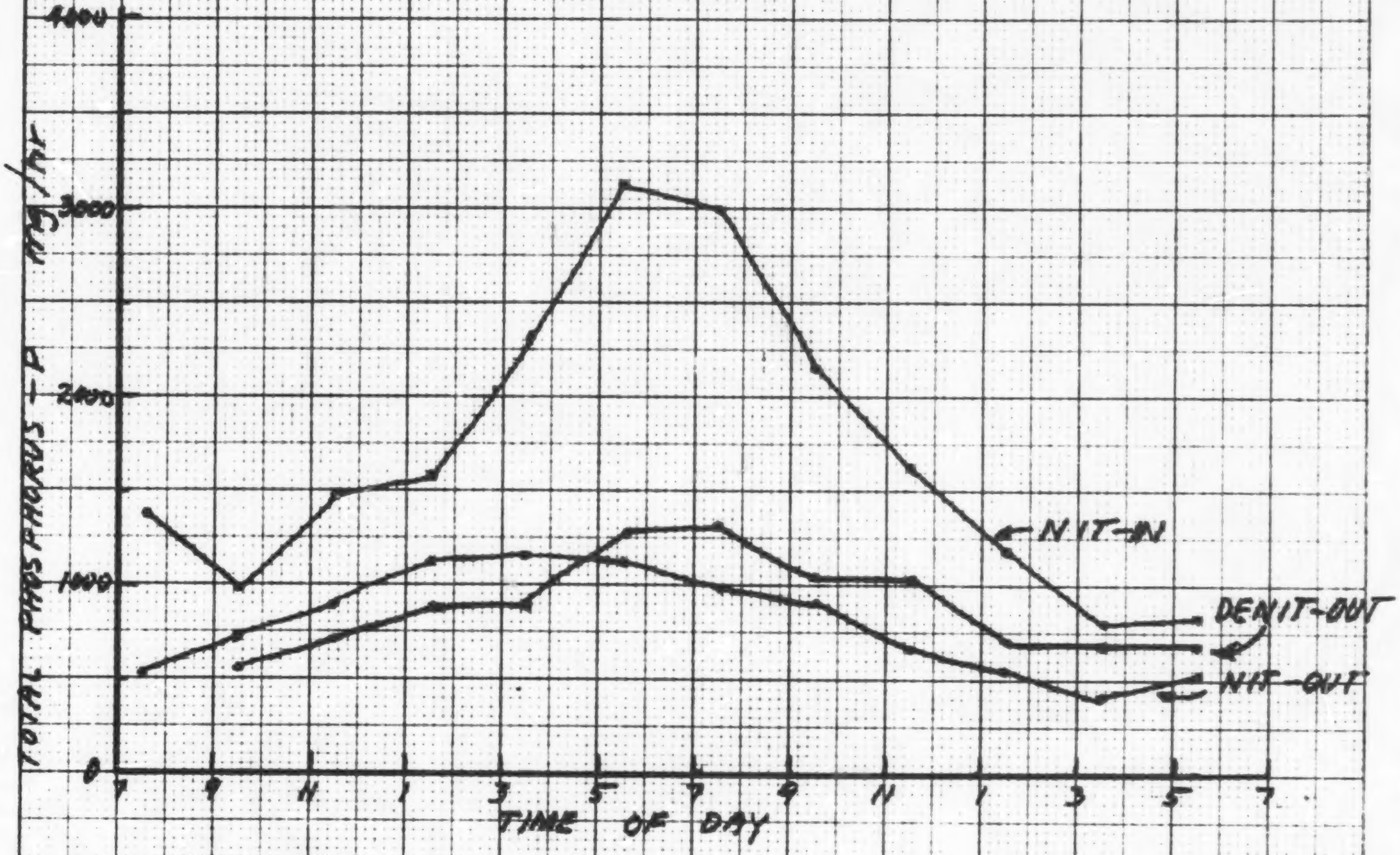
NITROGEN LOAD CURVES JUNE 19-20, 1969 FIGURE 45



COD & TOC LOAD CURVES JUNE 19-20, 1969 FIGURE 46



NITROGEN LOAD CURVES JULY 10-11, 1969 FIGURE 47



PHOSPHORUS LOAD CURVES JULY 10-11, 1969 FIGURE 48 presented graphically in Figures 43-48. Although all of the data collected are presented in the tables and figures, the following discussion will be limited to the June and July data for variable flow conditions only.

b. Discussion

(1) General Observation

No attempt at this time will be made to describe the trends in the data using a mathematical model. Only general observations with the probable significance of such will be made.

Output concentrations from the reactors are a function of the input concentrations, physical and biological mechanisms effecting treatment in the units, and the flow variations to the processes. In these tests the continuous use of a municipal wastewater at its source provided continuously varying input concentrations. Flow variations were imposed on the process by intentional and continuous variations in the pumping rates.

The data from each of four tests conducted in June and July as described above are shown graphically in Figures 27,29,30,31 and 32. These data are also shown in Figures 34, 36, 38, 40 and 42, where they are grouped together with similar data from other tests. Since the January data shown on these figures are not considered to be significant it should be ignored when evaluating the data. As described previously, mass flow curves for these tests are presented in Figures 43, 44, 45, 46, 47 and 48.

Aside from the low values found on July 10, the ammonia-N concentrations in the primary effluent as presented in Figure 34 showed an unexpectedly small diurnal variation, and the mean daily concentrations were quite similar. The majority of these concentrations varied between 12 and 16 mg/l.

(2) Nitrification Process

As described above, the input ammonia concentrations to the activated sludge process which accomplished the nitrification were reasonably constant. It is important to note the operating conditions of the activated

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sludge plant as shown in Table 12 (Test 18). A reasonably long mean detention time of 8.3 hrs was used, and the BOD/MLVSS ratio was quite low at 0.17. With these very conservative operating parameters the effect of flow should be less evident that if shorter holding times and higher BOD/MLVSS ratios would be used. Under these particular conditions of operation the output ammonia concentrations were generally less than 1.5 mg/l and quite constant throughout the 24-hour period. Essentially complete nitrification was being obtained.

The nitrate concentrations showed more of a diurnal variation than the ammonia. From similar earlier tests it was observed that with a constant input ammonia concentration the output nitrate concentrations seemed to vary inversely with the flow rate. A similar observation may be made with these data. The nitrate concentrations seem to be minimal during the high flow periods and higher during the low flow periods. Again this implies an increased assimilation of ammonia during the high load period which consequently leaves less remaining to be oxidized. This observation is somewhat reinforced by observing the load (or mass flow) curves where the ordinate difference between the input ammonia and output nitrate curves are far more during the high flow period than during the low flow.

The COD and TOC concentrations were quite constant and of low concentrations during the test on June 19-20.

(3) Denitrification

Except for the test on July 10-11, the primary effluent pumped to the denitrifying unit as the carbon source was not in phase with the flow to the nitrification plant. On the basis of the load curves it may be said in retrospect that it would be desireable to keep these flows in phase.

Although the mean BOD/N ratio used in the tests was higher than that considered optimum, the excess BOD applied was very likely not so much as to mask the variation in the input nitrate load. From the nitrate output curves for the denitrification units it is evident that insufficient carbon was supplied to the denitrification plant during these periods when the input nitrate load was the greatest. This is shown by the consistent and incomplete denitrification during these periods. When the main plant flows were at a minimum sufficient carbon was supplied to minimize the output nitrates. In the test on July 10-11 when the two flows were in phase the nitrate concentration was consistently low at less than 1.0 mg/l.

In all of the tests there was a cyclic variation in the output ammonia concentration from the denitrification process. In the June tests when the two flow rates were not in phase the ammonia concentrations varied approximately with the flow rate of the raw waste to the denitrification unit. It is possible that there was a deficiency in nitrate to satisfy the higher rates of metabolism during the periods when the carbon load to the denitrification unit was the greatest. As a consequence of this the growth and uptake of ammonia was limited once the nitrates were depleted (at a low level) and the effluent ammonia concentrations increased accordingly. In contrast to this in the July test when the two flows were in phase, the growth process was not nitrate-limited during the high load period and the effluent ammonia concentration showed considerably less variation and, in fact was a minimum during the high load period. With a carbon source free of nitrogen (e.g. with methanol) such variations would not exist, but the implications of growth and effect on the effluent in terms of COD, or BOD, or soluble carbon would be similar.

Phosphorus data obtained during the July 10-11 test show similarities to the ammonia data. Essentially little or no phosphorus is removed in the denitrification process. Effluent COD and TOC values were higher during the June 19-20 test in the denitrification process than in the nitrification plant effluent. This could very likely be remedied by employing a lower BOD/N ratio.

Overall it may be concluded that it is essential to use a proper BOD/N ratio during the complete flow cycle, and if done properly a completely denitrified effluent may be obtained. The mean holding time used to accomplish this (see Table 12, Test 18) was 1.3 hours in the mixing tank and very likely an even shorter time could be used.

VII. CONCLUSIONS

It has been shown that complete mixing biological waste treatment systems may be operated in series with a municipal wastewater to remove nitrogen by nitrification followed by denitrification. The activated sludge process used for nitrification was operated at non-critical loading rates and consequently optimum operating conditions cannot be recommended. Aeration times of 7-9 hours were used together with appropriate MLSS concentrations to produce completely nitrified effluents at temperatures as low as 10-12°C. Variable flow to the units did not change the effluent quality from that obtained with constant flow conditions. It is virtually certain that a municipal treatment plant operated as described above will produce an effluent in which the soluble nitrogen is in the nitrate form except for an ammonia-N fraction of less than 1.0 mg/l. Even with variable flow rates the ammonia-N concentration should not exceed 1.0 mg/l at any time.

Denitrification was obtained with a mean reaction tank detention time of 1.3 hours at 20°C and in 2.6 hours at 10°C temperatures. Effluent quality was essentially the same whether constant or variable flow was used. The effluent characteristically had a BOD concentration less than 20 mg/l and although the SS concentration were generally higher it is believed that these high concentrations were due to adverse hydraulic effects in the particular separation facilities used. The soluble ammonia-N in the effluent was shown to be almost solely due to the nitrogen added with the carbon source to the denitrification reactor. By using a nitrogen-free carbon source an effluent practically devoid of nitrogen may be obtained.

The extent of denitrification was shown to be dependent on maintaining a constant BOD/N ratio to the denitrification system. High ratios would produce a high carbon (BOD) concentration in the effluent and low ratios would result in incomplete denitrification. The ratio should be kept constant on an hourly basis and this may be accomplished by keeping the ratio of the two raw flow rates the same at all times. The effluent nitrate concentration may be kept well below 1.0 mg/l.

The rate of nitrate reduction in terms of mg N/g MLSS/hr was shown to be a linear function of the sludge loading rate, BOD/MLVSS.

BIBLIOGRAPHY

1. Johnson, W. K., "Nutrient Removals by Conventional Treatment Processes". Proc. 13th Ind. Waste Conf., Purdue Univ. Ext. Ser. 96, 151 (1958).

2. Johnson, W. K. and Schroepfer, G. J., "Nitrogen Removal by Nitrification and Denitrification". Jrl Water Poll. Cont. Fed., 36, 8, (1964) p.105.

3. Christianson, C. W., Rex, E. H., Webster, W. H., and Vigil, F. A., "Reduction of Nitrate Nitrogen by Modified Activated Sludge". U.S. Atomic Energy Commission, TID-7517 (Pt.1a), 264, (1956).

4. Bringmann, G. and Kühn, R. "Rapid Nitrification of Municipal Sewage with Mineral Carrier Sludge". Gesundheitsingenieur, 88, p.186-187, 1967.

5. Wuhrmann, K., "Objectives, Technology and Results of Nitrogen and Phosphorus Removal Processes. Univ. Tex. Water Resour. Symp., 1968, No. 1, 21-48.

6. Haltrich, W., "Elimination of Nitrate from an Industrial Waste". Proc. 22nd Ind. W. Conf., Purdue Univ. Eng. Ext. Series No. 129, 1967, p.203.

7. Barth, E. F., Brenner, R. C., and Lewis, C. F., "Chemical-Biological Control of Nitrogen and Phosphorus in Wastewater Effluent". Jrnl Water Poll. Cont. Fed., 40, 12, 2040, (1968).

8. Ludzack, F. J., and Ettinger, M. B., "Controlling Operation to Minimize Activated Sludge Effluent Nitrogen. Jrl. Water Poll. Cont. Fed., 34, 9, 920 (1962).

9. Balakrishnan, S., and Eckenfelder, W. W., "Nitrogen Relationships in Biological Treatment Processes. III. Denitrification in the Modified Activated Sludge Process. Wat. Research, 1969, 3, 177-178.

10. Mulbarger, M. C., Page, G. L., Yates, O. W. and Sharp, N. C., "Manassas Va. Adds Nutrient Removal to Waste Treatment". Wat. Wastes Engng, 1969, 6, No. 4, 46-48.

11. McCarty, P. L., Beck, L., and St. Amant, Percy, "Biological Denitrification of Wastewater by Addition of Organic Materials". Presented at 24th Annual Purdue Industrial Waste Conference, Purdue University, Lafayette, Indiana, May, 1969.

12. Verhoeven, W. "Some Remarks on Nitrate and Nitrite Metabolism in Microorgansms". A symposium on Inorganic Nitrogen Metabolism. The John Hopkins Press, Baltimore, 1956.

13. Bremner, J. M., and Shaw, K., "Denitrification in Soil". J. Agri. Sci., 51(1), 21-51, (1958).

14. Downing, A. L., Painter, H. A., and Knowles, G. "Nitrification in the Activated Sludge Process". J. Proc. Inst. Sew. Purif., 1964, 130.

15. McKinney, R. E. "Mathematics of Complete-Mixing Activated Sludge". Jrl. San. Eng. Div., ASCE, 88, SA3(1), 87, 1962).

16. Eckenfelder, W. W. and O'Connor, D. J. Biological Waste Treatment. Pergamon Press (1961).

17. Schulze, K. L. "The Activated Sludge Process on a Continuous Flow Culture". Water Sewage Works, Dec '64, Jan '65.

18. Smith, R., and Eilers, R. G. A Generalized Computer Model for Steady-State Performance of the Activated Sludge Process. U.S. Dept. Interior, FWPCA, Adv. Waste Treatment Br., Div. of Research, Cincinnati, Ohio, (1969).

19. Hadjëpetrou, L. P. and Stouthamer, A. H. "Energy Production During Nitrate Respiration by Aerobacter aerogenes". J. Gen. Microbiol. (1965), 38, 29-34.

20. Painter, H. A. "A review of Literature on Inorganic Nitrogen Metabolism in Microorganisms". Water Research, 4, 393, (1970).

21. Chang, J. P. and Morris, J. G. "Studies on the Utilization of Nitrate by Micrococcus denitrifications". J. Gen Microbiol. (1962), 29, 301-310.

22. Schroeder, E. D. and Busch, A. W. "The Role of Nitrate Nitrogen in Bio-Oxidation". Jrl. Water Poll. Cont. Fed., 40, 11, (1968) R445.

23. Downing, A. L. and Wheatland, A. B. "Fundamental Considerations in Biological Treatment of Effluents". Trans. Instn. Chem. Engrs., 40. (1962).

24. Eckenfelder, W. W. "A Design Procedure for Biological Nitrification and Denitrification". Chemical Engineering Progress Symp. Ser., No. 78, 63. p.230-234, 1967.

25. Tamblyn, T. A. and Sword, B. R. "The Anaerobic Filter for the Denitrification of Agricultural Subsurface Drainage". Presented at the Twenty-fourth Annual Purdue Ind. Wastes Conf., Purdue Univ., Lafayette, Ind., 1969).

26. Seidel, D. F. and Crites, R. W. "Evaluation of Anaerobic Denitrification Processes". Jrnl of the San. Engr Div., ASCE, 96, SA2 (1970).

27. Bruce, A. M., Boon, A. G. "Aspects of High-Rate Biological Treatment of Domestic and Industrial Waste Waters". Presented at Congress of Public Works and Municipal Services, London, 1970.

28. Heukelekian, H. and Rand, M. C. "Biochemical Oxygen Demand of Pure Organic Compounds". Sewage and Ind. W. 27, 9, 1040 (1955).

29. Standard Methods for the Examination of Water and Wastewater, 12th Edition, American Public Health Association, 1965.

30. Menzel, D. W., Corwin, N. "The Measurement of Total Phosphorus in Seawater Based on the Liberation of Organically Bound Fractions by Persulfate Oxidations". Limnology and Oceanography, Vol. 10, No. 2, p.280, April 1965.

31. Gales, M. E. Jr., Julian, E. C. and Kroner, R. C. "Method for Quantitative Determination of Total Phosphorus in Water". JAWWA, Vol. 58, No. 1, p.1363, Oct. 1066.

32. Johnson, W. K. "Automated Variable Flow for Pilot Plants". Environmental Science and Technology, Vo. 4, No. 1, p.68, Jan. 1970.

33. Johnson, W. K. and Schroepfer, G. J. Nitrogen Removal from Wastewater by Biochemical Nitrification and Denitrification. Final Report PHS Res. Grant WP-225, University of Minnesota, April 1963.

34. Downing, A. L. and Hopwood, A. P. "Some Observations on the Kinetics of Nitrifying Activated-Sludge Plants". Schweiz. Zeits. Hydrol. 26, 271, 1964.

35. Garrett, M. T., Jr. "Hydraulic Control of Activated Sludge Growth Rate". Sew. and Ind. W., Vol. 30, No. 3, p.253, Mar 1958.

36. Moore, S. F., and Schroeder, E. D. "An Investigation of the Effect of Residence Time on Anaerobic Denitrification". Water Research, Vol. 4, Oct 1970, p.685-684.

37. Pöpel, F. "Criteria for Evaluating the Effect of Waste Waters on Receiving Waters". Vatten, 1967, 23, 17-34.

38. Hamm, A. "Nitrification and Denitrification in Biological Sewage Treatment". Münchn. Beitr. Abwass. -Fisch. -u. Flussbiol., 1968, 5, 331-338.

39. Nilsson, E. S. and Westberg, N. "Bacterial Denitrification of Nitrate Containing Waste Waters". Vatten, 1967, 23, 35-40.

40. Schmidt, B. and Kampf, W. D. "The Influence of Oxygen in the Denitrifying Efficiency of Pseudomonas Fluorescens". Arch. Hyg. Bakt., 1962, 146, 171-182; Lit Ber. Wass. Abwass Luft.u. Boden, 1962/63, 11, 275.

41. Bringmann, G. and Kühn, R. "Semi-Technical Stabilization and Intensification of Denitrification". Gesundheitsing., 1964, 85, 19-22.

42. Bringmann, G. and Kühn, R. "Controlled Denitrification of Surface Waters by Hydrogen-Oxidation". Gesundheitsing., 1963, 84, 213-215.

43. Haltrich, W. and Jäger, B. "Observations on the Biological Treatment of Nitrate-Containing Trade Waste Water by the Denitrification Process in an Activated-Sludge Plant". Gas -u. Wasserfach, 1963, 104, 347.

44. Mudrack, K. "Nitro-Cellulose Industrial Waste". Proc. of 21st Ind. W. Conf. Purdue Univ., Engng Extn Ser. No. 121, 1966, 656-664.

45. Sample, W. R. "Removal of Nitrogenous Compounds from Waste Waters". Chem. Engng Progr. Symp. Ser., No. 78, 63, p.223-229, 1967.

46. Hünerberg, K. and Sarfert, F. "Experiments in the Elimination of Nitrogen from Berlin Sewage". Gas -u. Wass Fach, 108, 966-969, 1197-1205, 1967.

47. Echelberger, W. F. and Tenney, M. W. "Waste-Water Treatment for Complete Nutrient Removal". Wat. Sewage Wks, 116, p.396-402, 1969.

48. Bringmann, G. and Kühn, R. "Rapid Denitrification by the Negative-Pressure Process". Gesundheitsingenieur, 1965, 86, 16-19.

49. Johnson, W. K. "Removal of Nitrogen by Biological Treatment". Univ. Tex. Wat. Resour. Symp., 1968, No. 1, 178-189.

50. Das, A. C., Jhan, J. A. and Dutta, B. K. "Removal of Nitrogen from the Fertilizer Factory Effluent by Biochemical Nitrification and Denitrification". Technology, Sirdri, 1965, No. 1, 10-14.

51. Wuhrmann, K. "The Removal of Nitrogen and Phosphorus Compounds from Domestic Sewage. Results of Experiments on a Technical Scale". Schweiz. Z. Hydrol., 1964, 26, 520-558.

52. Wuhrmann, K. "Nitrogen Removal in Sewage Treatment Processes". Verh. int. Ver. Limnol. 1962, 1964, 15, 580-596.